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DIASTROPHISM AND THE FORMATIVE PROCESSES. III

THE LATERAL STRESSES WITHIN THE CONTINENTAL PROTUBERANCES AND THEIR RELATIONS TO CONTINENTAL CREEP AND SEA-TRANSGRESSION

T. C. CHAMBERLIN
University of Chicago

In the second article of this series—preceding number of this *Journal*, pp. 517–33—it was urged that ordinary diastrophism springing from internal stresses is, in its very nature, unsuited to adjust the surface of the earth to the surface of the sea over wide areas with such close nicety as effectively to facilitate the great sea-transgressions and the formation of the great terranes of marine sediments that spring from them. This inadaptability is held to arise chiefly from the fact that the deforming earth-stresses, on the one hand, and the working relations of the sea-surface to the sea-shelves, on the other, are so far independent of one another in origin and mode of action that they are not naturally co-operative in so close and harmonious a way as to be suited to produce the observed results, since these are obviously the effects of nicely adjusted relations.

So, too, it appeared that such vertical stresses as may arise from loading and unloading in the process of gradation are unsuited to produce these results, because loading and unloading tend to produce a warp between the loaded and the unloaded tracts,

whereas great sea-transgressions and great terranes of parallel sediments require either a movement that retains the parallelism of the sea-surface and the sea-bottom, or else the essential absence of any movement at all. A constant upwarping of the land inevitably defeats extensive sea-transgression and its consequent terranes.

In further pursuing the conditions that favor or oppose great sea-transgression and the formation of the great parallel terranes of marine strata, we have now to consider the unbalanced stresses that inevitably arise *within* the continents as a consequence of their own protrusions. These are to be distinguished from the internal stresses of a more general nature that are usually regarded as the cause of orogenic and epeirogenic movements which are here covered by the phrase, ordinary diastrophism. The stresses that arise within the continents simply because they protrude above the ocean beds are of a much more special and limited class. These stresses depend simply on gravity acting on the protruding matter as such without regard to other conditions; they are strictly inevitable and in the main independent. If the base on which the continents rest were absolutely inflexible, lateral stresses would arise within the continents from their gravitative pressures on their own masses, just as such stresses arise in continental glaciers and actuate them. If, on the other hand, the continents floated on a molten interior, or were in any other way kept in a continuous state of isostatic adjustment—in the usual sense of isostasy in which each column equals every other column in radial pressure—there would still arise within the protuberances unbalanced *lateral* stresses in proportion to the degree of protrusion.

It is perhaps necessary to remark here for the sake of complete clearness that isostasy, in the most complete and unlimited sense of the term, involves equal pressures in *all* directions, not merely equal pressures in vertical directions. Equal pressures in all directions are predicable only of perfect fluids. In this radical sense, the earth cannot be in complete isostatic adjustment at the present time because of its inequalities of surface and because of the differences in the lateral distribution of specific gravity in its crust, even if every vertical column balances every other vertical column perfectly. If the earth were ever in a complete

molten state—a view I do not now entertain—it would no doubt have assumed a state in which the lateral pressures would have been strictly equal and the vertical pressures also equal at any given depth, though of course varying with depth. The isostatic conditions would doubtless then have been complete and perfect in this radical sense, if we neglect such modifications as might have arisen from convection and similar internal disturbing activities. There should then have been a closely concentric arrangement of material according to its specific gravity, a uniformly level surface, and a universal ocean of uniform depth, as logically pictured by our geologic forefathers. This beautiful picture, were it true, would seem at first thought greatly to simplify the dynamic and diastrophic problems of the earth body, but in fact it forces upon us at once a problem of grave difficulty, the problem of finding a really rational way in which an earth, starting with such a symmetrical organization, could have passed into an earth with such irregularities of form and substance, and such differentiations of specific gravity as are actually presented by the existing earth. The depth to which the specific gravities of the continents and the sub-oceanic segments have recently been found to differ presents a new and formidable difficulty. The recent revival of the doctrine of isostasy, on the basis of geodetic data,[1] appears to have been regarded in some quarters as lending fresh support to the inherited view of a liquid earth, but in reality the results reached greatly augment a difficulty which had never been met with full success: the mode by which a horizontal differentiation of specific gravity in the outer part of the earth body could take place on a large scale, together with the mode by which the continental swells and the oceanic sags could be initiated and maintained. These great inequalities can be sustained only by adequate powers of resistance to the lateral stresses that tend to equate them and must always have tended to equate them. How such differentiations could have been forced upon a globe once in a fluidal condition—from which these

[1] The "Figure of the Earth and Isostasy from Measurements in the U.S. Coast and Geodetic Survey," Washington, D.C., 1909, and other papers of John F. Hayford; see also G. S. Burrard, "On the Origin of the Himalaya Mountains, a Consideration of the Geodetic Evidence," *Prof. Paper No. 12, Survey of India*, Calcutta, 1912; also *Geol. Mag.* Dec. V, Vol. X, No. 9 (September, 1913), pp. 385–88.

differentiations were necessarily absent—against the great stress-differences involved, is an obdurate problem that now takes on a new and definite aspect because of the very considerable depth to which the differentiation of specific gravity is found to extend. This, however, is not a problem to be discussed here; its solution is the task of those who entertain the view of the former fluency of the earth. The question is serviceable here by way of giving emphasis to the lateral stresses that inevitably exist in a protruding continental body due to its own gravity. If the continents were instantly converted into a molten condition they would flow at once and with violence toward an isostatic state and give a catastrophic illustration of the difference between the present state and a complete isostatic state.

The nature and the intensity of the lateral stresses in the continental protuberances may be easily visualized by means of an analytical picture of the continents and the great basins. Let these be assumed to be in isostatic equilibrium in the limited sense of the term as commonly used and let the protuberances be divided into independent vertical prisms of uniform dimensions. Then, if we choose to take the isostatic flotation view, each prism will float freely at a height inversely proportionate to its specific gravity, assumed to be the present height; or, if we prefer the solid isostatic view, each prism exerts the same pressure as each other prism on its base at the level of compensation. If the prisms be viewed as independent of one another, they must be sustained against the tendency to spread and collapse under their own gravity by a rigid coherent force acting transversely and equal at each point to the gravitative pressure at that point. This pressure is easily computed. If for this purpose we take the very conservative reliefs of 6,000 feet for the summit swells of the continents and of 12,000 feet for the bed of the ocean, the relief-difference will be 18,000 feet. This is not half the extreme actual differences but may perhaps fairly represent the continents if they were reduced to symmetrical swells. If we assume a specific gravity of 2.7 for continental rock, the gravitative pressure of the base of a prism rising from the horizon of the ocean bed to the border of the continents at sea-level, 12,000 feet, would not be far from 14,000 pounds to

the square inch. Over against this would be the pressure of 12,000 feet of water or roundly 5,000 pounds to the square inch, leaving a differential pressure of 9,000 pounds to the square inch, which may be taken as representing the pressure at the base of the border prisms of the continent. The prisms that would form the summits of the continental swells, taken at 6,000 feet above the sea-level, would suffer a differential pressure of about 16,000 pounds per square inch at their bases. Now unbalanced pressures of 9,000 to 16,000 pounds per square inch are equal to the crushing strength of weak rock and approach that of average rock. Oblique or transverse shearing would not unlikely take place in a prism of rock instead of crushing and this would require appreciably less stress, but just how much less has not been well determined as yet, so far as I know. There would be, at any rate, at the base of each such ideal prism of the continents, internal stresses that would approach the average strength of the rock of which they were composed and, in the weaker cases, would probably exceed it.

If now, instead of our idealized continental swells, we take the actual case, the stresses will be found much more intense. For example, the present Tibetan plateau over a wide area has an elevation of 15,000 feet or more above the sea-level, and the ocean bed, not far away, is considerably more than 12,000 feet in depth, so that after allowing for the oceanic pressure, there would be at the base of a Tibetan prism an unbalanced lateral pressure of 25,000 or 30,000 pounds to the square inch. In an isolated column this would be opposed only by the rigidity of the rock, and if this were of the average type, creep would certainly take place in the lower portion, if crushing did not anticipate it. The phenomenon of creep in mines and canyons under much less pressure leaves no room for doubt on this point.

But massed as the ideal prisms actually are in the continents, and surrounded by low slopes running out under the edges of the oceans, the actual case presents a modified aspect. The prisms not only lend some support to one another—though they must then carry one another's burden in some degree—but the sub-marine continental slopes buttress them. These buttresses are subject to lateral pressures of their own, but in so far as these pressures

fall below the creep pressure the residue of the strength of the buttresses opposes continental creep. The sub-oceanic buttressing is subject to further qualifications whose natures are more or less uncertain. The substructure of the border slopes of the continents is unknown. To some geologists, the preferred picture of the continental borders is that of fault scarps with slopes of incoherent sediment banked against these. To others, it is that of warps or folds of indurated rock below with sheets of recent sediments above and banks of recent sediments on their outer borders. To still others, the picture is that of a graduated sedimentary series, soft and incoherent at the surface and on the abysmal face, grading downward and backward into more and more indurated rock. This may or may not be more or less warped and compressed by thrusts from the ocean bed, according to situation. There are no doubt other conceptions. The continental borders present a suggestive field for study which has not yet been adequately cultivated.[1] It would be a diversion from our main purpose to enter into a discussion of the details of the continental borders here, but, though opinions are diverse in other respects, they are at one on two features that bear on this discussion: (1) some notable portion of the border material is soft and feebly coherent, and (2) the borders of the continents have been specially subject to deformative processes throughout geological history and were hence probably weakened in their resisting powers thereby through the development of shear planes. There is good reason to believe also that creep takes place in the more recent soft material, whatever may be true of the indurated parts of the continental protuberance as a whole.[2] These considerations make it difficult to judge how far the buttressing of the continents by the border slopes is effective in resisting the lateral pressure that tends to spread the protruding masses.

There is another consideration that affects the degree of resistance to lateral spreading in a possibly important way. It seems clear from an inspection of the folds of mountains that they are relatively superficial.[3] It is probable that a shear zone has been

[1] For some suggestions see Chamberlin and Salisbury, *Geology*, III (1906), 523–29.

[2] *Ibid.*, pp. 527–28. [3] *Ibid.*, II, 128.

developed beneath the shell when it has suffered orogenic movements and that this facilitated folding and at the same time tended to limit it below. The shear is probably distributive through some depth and covers the horizons at which the tendency to creep is chiefly felt. The shear planes thus formed by the forceful orogenic agencies may serve as planes of movement for the less forceful creep afterward. The occasion for creep springs in some part from the elevation involved in the folding and allied diastrophic processes, and the creep itself is of the nature of a reversal of the elevating process, and so it may not unnaturally be facilitated by the shear planes already developed by the antecedent diastrophism.

Complicated by these modifying factors whose values are uncertain, it does not appear that the problem of creep is at present susceptible of satisfactory computative treatment; it can be dealt with now only in a naturalistic way on the basis of the evidence and the probabilities of the case. In time, when suitable geodetic surveys shall have been repeated, there will come positive demonstration. The creep movement, if it is appreciable, must result in a spreading of the geodetic stations, and exact measurements after sufficient intervals will give unequivocal evidence of the movement or of its absence, as also of its nature and its rate. Some few first steps in this direction have already been taken; notably the geodetic re-survey of the region of the recent California earthquake. Horizontal strain followed by horizontal movement were there shown, but they were too limited and their interpretation too uncertain to contribute much to the general question of creep. The demonstration that the movement was horizontal is, so far forth, favorable. The recognition that this and certain other earthquakes were due to differential horizontal movements—in distinction from the vertical movements to which earthquakes have generally been referred—is perhaps a step toward the demonstration of a wider system of horizontal movements of secular prevalence.

It would be going too far from our immediate purpose to set forth in full the phenomena that seem to point to glacier-like continental creep as one of the prevailing movements of the earth's crust. We are here merely seeking its possible effects on sea-transgressions and the stratigraphic terranes dependent on these.

The nearly universal presence of gaping crevices over the whole face of the continents, affecting all classes of rocks, is quite in harmony with a general spreading movement and has not otherwise found an altogether satisfactory explanation. Supporting this also is the prevalence of tensional faulting to so great a degree that it has gained the name *normal* faulting.[1]

It can hardly be supposed that such lateral stresses as must exist within the continents from the nature of the case, can fail to produce some effect, since changes of various sorts are going on within the continents, particularly molecular changes stimulated by heat, pressure, and other forces, and these must be influenced by the lines of least resistance imposed by the differential stresses. The vital question is whether this is a matter of geologic consequence or not. We must apparently wait for a decisive answer, and in the meantime treat the possibility of effective creep hypothetically.

The point of special interest in this discussion is the bearing which the hypothetical glacier-like creep of the continents has on such an adjustment of the land surface to the sea-surface as promotes systematic shelf-building and the development of shelf-seas as set forth in Article II of this series. We have found that ordinary diastrophic movements are, in the main, inimical to the close adjustments required. Continental creep is, however, regarded as essentially independent of ordinary orogenetic or epeirogenetic diastrophism; indeed it is regarded as, in a sense, their reversal. Its action is suspended or overwhelmed by movements in the opposite direction when a diastrophic revolution is in progress. It is only when ordinary diastrophism is quiescent and the continents are in their relatively static stages that the slow, gentle reactionary movement of creep is presumed to be appreciable.

Now this is not so much a vertical movement as a horizontal one, though actuated by gravity. It is indeed downward in a degree but it is horizontal in its main expression. By reason of this, it is fitted to become a copartner with gradation in leveling the land and thus facilitating an advance of the sea. It is in itself a massive form of gradation; it works toward a base-level of its

[1] For a discussion of creep in relation to faulting, see T. C. Chamberlin, "The Fault Problem," *Economic Geology*, II, No. 8 (1907), 709–21.

own. While I think its molecular methods are distinctly different from those of a true plastic body, the result is a continental spreading out and flattening down whose aspect is almost identical with that of a plastic body. A block of asphaltum will spread and flatten for years but it finally reaches a state beyond which the movement will not go. It reaches a base-level of a certain sort. So the continents, under the action of glacier-like creep, however great its efficiency may be supposed to be, will merely flatten out to a certain extent and the resulting surface will ideally be of the nature of a sloping plain closely analogous to the peneplain produced by erosive degradation.

So far as creep may be supposed to affect the continental shelf it moves it outward and slightly downward, and this fits the shelf surface for the reception of more sediments. If the downward component of the movement were greatly in excess of the rate of sedimentation, it would carry the shelf out of good working adjustment, much as in the case of ordinary diastrophism, but it seems highly improbable that the creep movement depresses the surface of the continental shelf faster than sedimentation naturally builds it up, even when the general continental creep is supplemented by the special creep in the soft sediments of which the younger upper and outer portions of the shelf are formed. The work of creep in thus pushing the shelf outward and slightly downward relieves wave-action of a part of its burden in building out the shelf and so enhances the joint effect. It seems safe therefore to regard creep as a co-operating adjunct to both parts of the gradational work, the leveling of the lands and the building-out of the shelves.

The outward creep of the continents reduces the capacity of the ocean basins and thus aids in lifting the sea-level and forcing the waters to creep out upon the lowered land. In this way also it co-operates with erosive gradation, which by transferring a portion of the land to the sea in another way raises the sea-level and causes its advance on the land.

While the great sea-transgressions—and the great terranes of parallel strata to which they gave rise—imply a relative freedom from diastrophism while forming, the details of bedding and

faunal distribution give evidence of minor oscillations, of advances and retreats of the sea, of shiftings of outlines, and of changes of barriers and connections, the effect of which is to introduce special features in the sedimentation and local or regional variations in the faunas. These features were subordinate to the grander deployments both in area and in time, and in this subordination they suggest that they may have been due to minor and perhaps separate agencies that acted more continuously and in smaller units —more easily and variously shifted—than the profound deformative agencies that were liable to interrupt the whole process. Gentler agencies whose general activities were harmonious with the main sedimentary process seem better fitted for this function than a supposed feeble action of a titanic agency whose normal action would put an end to the whole process.

There is an aspect of continental creep, if we may follow the analogy of glaciers, that seems to fit it for this function. The suggestion is at least worth entertaining and testing as a working hypothesis. The creeping body of a glacier does not always decline steadily in the direction of its motion but rather assumes a more or less undulatory mode of progress. While the advancing surface, taken as a whole, slopes forward, it may, in a subordinate measure, slope backward, i.e., *rise* in the direction of its advance. On broad glaciers of nearly flat surfaces, there are sometimes swells and sags; the surface water sometimes gathers into lakelets, and occasionally streamlets of notable size flow in a direction *opposite* to the flow of the glacier beneath.[1] These anomalies are assignable to irregularities in the rock floor over which the ice mass is thrust by its internal stresses. The creep of a continental embossment, if it follows the glacial analogy, may be assigned a similar undulatory mode of progress. If continental creep is facilitated by a shear zone that had been formed previously by the powerful stresses that actuated the lateral crust movements of earlier times, the shear planes of the zone are not probably perfectly plane; they are much more probably undulatory, for the surface effects of the diastro-

[1] See T. C. Chamberlin, "Glacial Studies in Greenland," *Jour. Geol.*, II (1894), 784, Fig. 12, view of a portion of Blase Dale Glacier showing the undulation of its surface involving a backward inclination. For a backward flowing stream see Vol. V (1897), 231–32.

phism and probably the basal effects were undulatory. The glacier-like rock mass in being thrust by its own internal stresses over these undulatory shear planes—in effect an undulatory floor like that of the glacier—must probably have gently swelled and sagged as does ice under similar conditions. The sea, or any other water-body, lying upon this creeping undulating sheet would suffer shiftings of outline, changes of deposition, rises and removals of barriers, attended by variations of faunal development. While these might rise to some moment, and might seem to be epeirogenic in nature, they would not usually suspend the main progress of sea-transgression, but rather, on the whole, be tributary to it, whatever their temporary or local effect might be. If this source of minor oscillations shall ultimately find warrant, it will relieve us of referring these various slight intercurrent undulations of the surface to those deep-seated potent agencies whose normal action is refractory rather than compliant with the gradational agencies on whose well-adjusted action the development of the great stratigraphic terranes, as a whole, are dependent.

THE GENERAL PRINCIPLES UNDERLYING METAMORPHIC PROCESSES

JOHN JOHNSTON AND PAUL NIGGLI
Geophysical Laboratory, Carnegie Institution of Washington

PART II

THE PHASE RULE

The phase rule, which recently has been applied to metamorphic rocks,[1] orients us as to the number of phases which, for a given number of components and for given external conditions, can be in equilibrium with one another. According to the phase rule $f=c-n+2$, where f, c, and n are the number of degrees of freedom, of components, and of phases, respectively.[2] If f is zero, the system is stable only when temperature, pressure, and concentration (composition) of each phase have definite and singular values. If f is 1, a change of one of the above three parameters induces definite and definitely related alterations of the other two, if the number and nature of the phases is to remain unaltered. If f is 2, any two of the above parameters may be changed; such a system can exist at any pressure or temperature within certain limits, although under such circumstances the composition of all the phases present is at

[1] V. M. Goldschmidt, *Kontaktmetamorphose im Kristiania-Gebiet*, Kristiania, 1911, and in other papers; P. Niggli, "Chloritoidschiefer des nordöstlichen Gotthardmassives," *Beiträge geol. Karte Schweiz*, N. F., XXXVI (1912).

[2] "A heterogeneous system is made up of different portions, each in itself homogeneous, but marked off in space and separated from the other portions by bounding surfaces; these homogeneous, physically distinct, and mechanically separable portions are called *phases*" (Findlay, *Phase Rule*, p. 9).

"As the *components* of a system there are to be chosen the *smallest number* of independently variable constituents by means of which the composition of each phase participating in the state of equilibrium can be expressed in the form of a chemical equation" (*ibid.*, p. 12).

"The number of degrees of freedom of a system is the number of the variable factors, temperature, pressure, and concentration of the components, which must be arbitrarily fixed in order that the condition of the system may be perfectly defined" (*ibid.*, p. 15).

For a full discussion of these matters the reader is referred to Findlay's book.

any moment definitely fixed. Thus a system with two degrees of freedom can in general exist throughout a range of temperatures and pressures; if the system actually had only one degree of freedom, it could only be accidental if the corresponding values were chosen. Therefore the number of possible phases coexisting *in equilibrium* during metamorphic processes will in general not be greater than the number of components. The essentials of the phase rule and their application to simple systems are so readily understood that there is always a temptation to neglect their specific limitations; limitations which are especially prominent when, as in the case of metamorphic processes, we endeavor to reason backward from the end-result of the process.

Limitations to the applicability of the phase rule to metamorphic systems.—Application of the phase rule presupposes that the pressure (and temperature) is uniform throughout the system[1]. Now it is clear that absolutely uniform pressure (or temperature) can never occur during rock metamorphism; we may have anything from great inequality in the stresses in the three principal directions to a nearly equal distribution of the three stresses. On the relative and absolute magnitude of the variation of the resultant stress from point to point depends its influence on the result. If the particular paragenetic transformation can still go on in spite of considerable variations of either temperature or pressure from the mean values which actually obtain, it will not be much affected by the local stress variation; if otherwise, great local variation of results may be expected. Moreover, similarly variable results will be produced by the changes of temperature and pressure which accompany the process of metamorphism.

Reference to the discussion of phases and components given in the textbooks renders it evident that great caution must be exercised in guessing (inferring) the actual components from an examination of the more or less ultimate state of any given rock. It is an essential property of a component that it is always in reaction with the other members of the system throughout the establishment of equilibrium. But the fact that under laboratory conditions

[1] Further, that there are (*inter alia*) no surface effects; this condition might be unfulfilled in certain cases, e.g., with very porous rock-masses.

a component is so insoluble that its rate of reaction seems so small as to be negligible does not prove that in geological phenomena, for which unlimited time is available, the influence of such a component can be neglected. Moreover, the similarity in chemical nature of certain oxides does not justify grouping them together as a single component, in an effort to simplify the system under consideration; for the behavior of the numerous two-component systems hitherto studied shows that the grouping-together of the oxides of the alkalies, or of the alkaline earths, or of alumina and iron, is of doubtful validity.

By means of the microscope it is often possible to distinguish between original and new components. The presence of any original components which could not have been formed by the metamorphic process indicates that the forces were not intense enough, or did not last long enough, to render the alteration complete; we have then an incompletely metamorphosed rock. On the other hand, the presence of original quartz grains alongside new quartz (as is frequently observed) is no proof of incomplete metamorphism, because quartz, which is stable throughout a very wide range of conditions, may appear in spite of considerable variation of chemical composition, temperature, or pressure. Again, it is a question of the stability of the new forms. When one recalls how frequently metastable forms appear in laboratory work and considers the special circumstances of metamorphism, one need not be surprised if metastable substances occur frequently in nature also even though the conditions of formation remain undisturbed for long periods of time. Metastable forms are observed oftenest with polymorphic or hydrated substances; their occurrence therefore in general changes only the nature, but not the number of the phases present. For instance, so far as the phase rule is concerned, it does not matter though kyanite appear instead of the stable sillimanite.[1]

Metamorphic processes are merely the result of a tendency toward a new equilibrium position; whether this new position of equilibrium is reached or not, depends, however, on a number of factors. It is a question if a rock as a whole can always be con-

[1] The *simultaneous* occurrence of both sillimanite and kyanite would of course increase the number of phases by one.

sidered as a single system, within which complete mutual actions and reactions are possible. This may well be so if the original rock was fairly homogeneous and not too coarse grained. In the case of rocks the solubility of most of the substances concerned is so small that contact with a small amount of material can suffice for the production of saturated solutions; and so the new material will be the same throughout such a system, although the amount of material in solution at any moment is small. But whether all of the original components, which by reason of the changed conditions have become unstable, disappear or not depends upon the rate of reaction, upon the time, and upon the presence of catalytic agencies; furthermore, if any of the components or intermediate or reaction-products are present as grains of appreciable size, they may become coated with some stable substance and hence—owing to the slowness (and even absence) of diffusion in the solid state—be protected against further action.

When to these circumstances which hinder the attainment of equilibrium we add the complications introduced by phenomena such as resorption,[1] the occurrence of reactions in the solid state (including monotropic and enantiotropic changes) and the existence of compounds which, while unstable on fusion, are able to form at lower temperatures; further, when we consider that some of the essential components may by reason of their volatility have escaped from the system and that the influence of pressure upon stability relations is practically unknown—when we remember this formidable array of possibilities, we should hardly expect to draw immediate or final conclusions merely through application of the phase rule in such complicated polycomponent systems as rocks.

Consequently, the phase rule cannot always be expected to hold rigidly or to serve in any manner as an "open sesame" in such studies. What we observe is that there appear, for a given metamorphic process and for a given number of components, only a limited number out of all the possible compounds; moreover, that the number of definite and important minerals formed by a metamorphic process usually does not exceed the maximum number

[1] For an example, see p. 593.

postulated by the phase rule. On the other hand, while in several cases the number of phases found does not exceed the number predicted from a consideration of the phase rule, on the specific assumptions that equilibrium has been reached and that the components have been correctly inferred, yet the presence of more or fewer phases than expected proves nothing except that the assumptions were wrong.

From the discussion of these limitations to the phase rule we conclude, therefore, that our present knowledge of the facts concerned is so scanty that the phase rule is not yet of much service in aiding us to describe the natural history of metamorphic rocks.[1] Nevertheless it may be of assistance in the classification of rocks; for this reason, and in order to emphasize by means of actual illustrations some of the statements made in the above paragraphs, we include a brief discussion of the application of the phase rule to ternary systems.

The ternary system—lime-alumina-silica.—The relative simplicity of two-component systems tempts one to assume that systems of three or more components may somehow be considered in an equally simple manner. That such is not the case is amply demonstrated by the lime-alumina-silica series, which has recently been very thoroughly investigated[2] at constant pressure.

From this work, in which the variables considered are only concentration and temperature, it follows that there are—instead of the simple ternary relation with a single ternary eutectic, such as the textbooks commonly treat—about eighteen invariant points (at which 3 solid phases coexist with 1 liquid phase) any one of which might under proper conditions show the usual eutectic properties (e.g., eutectic structure).[3]

[1] The phase rule will of course be an indispensable adjunct when the experimental facts are available.

[2] E. S. Shepherd and G. A. Rankin, "Preliminary Report on the Ternary System $CaO-Al_2O_3-SiO_2$," *Jour. Ind. Eng. Chem.*, III (1911), 211; *Z. anorg. Chem.*, LXXI (1911), 19.

[3] In passing it may be suggested that the so-called eutectic structure as inferred from the study of alloys may or may not occur in the case of silicates. It is readily conceivable that systems in no sense eutectic may easily yield the so-called eutectic structure and vice versa; cf. Shepherd and Rankin, *loc. cit.*

The provisional diagram given by Shepherd and Rankin is reproduced in Fig. 1; we shall make no attempt to discuss it here, except in regard to two points, viz., (1) the occurrence of resorption, and (2) the formation of very different end-products from systems of very similar original composition.

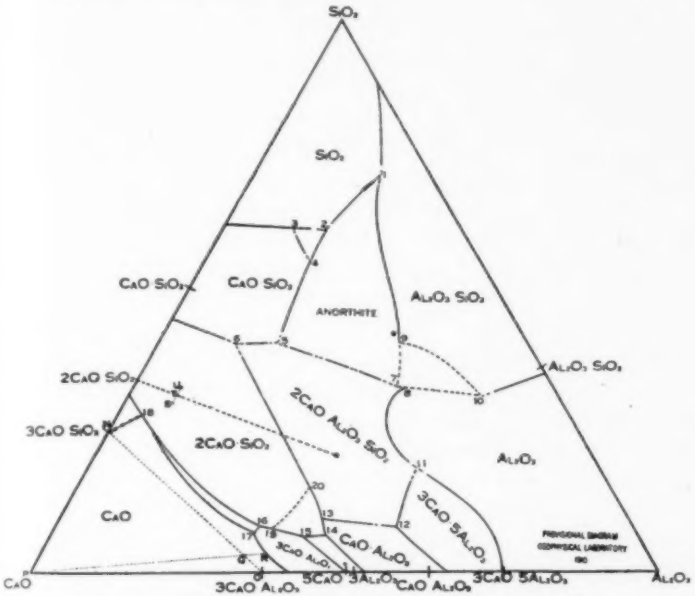


FIG. 1.—Provisional Diagram[1] for System $CaO \cdot Al_2O_3 \cdot SiO_2$

Consider a mixture the composition of which is represented by a point on the line *PQ*, and suppose it to be cooling. Lime crystals separate, the composition of the melt moves along the line *PQR* until the point *R* on the boundary curve *R*–17 is reached. At this point the solid phase ($3CaO \cdot Al_2O_3$) begins to separate, which is possible only by resorption of CaO; the composition of the melt

[1] The position of several of the points which were still doubtful at the time this diagram was published has now been more definitely established by further investigation, the results of which will appear in a forthcoming paper by Rankin. These changes, however, do not affect any of the deductions which appear in the paper of Shepherd and Rankin (*loc. cit.*).

moves along the boundary curve R–17 until the invariant point 17 is reached, when the whole solidifies to the three phases (CaO), ($3CaO \cdot Al_2O_3$), and ($3CaO \cdot SiO_2$). In this case only part of the free CaO is resorbed; but if the original composition had been represented by a point on the line QR (i.e., outside the triangle NOP) the CaO would be completely resorbed, the final crystallization occurring at invariant point 15, at which the phases ($3CaO \cdot Al_2O_3$), ($5CaO \cdot 3Al_2O_3$), and ($2CaO \cdot SiO_2$) are in equilibrium. All of these phenomena occur, be it noted, without interruption of the normal cooling or the intervention of any external disturbing factor.

As regards the second point, consider compositions along the line STU, the total length of which corresponds to a change of only 3 per cent in the amount of CaO present. Compositions on the line ST solidify at invariant point 16, 15, or 14, according to the original position on the line; the ternary grouping formed is either ($3CaO \cdot SiO_2$), ($2CaO \cdot SiO_2$), ($3CaO \cdot Al_2O_3$), or ($5CaO \cdot 3Al_2O_3$), ($3CaO \cdot Al_2O_3$), ($2CaO \cdot SiO_2$), or ($5CaO \cdot 3Al_2O_3$), ($2CaO \cdot SiO_2$), ($CaO \cdot Al_2O_3$). Compositions on the line TU solidify at point 6, forming the grouping ($2CaO \cdot SiO_2$), ($CaO \cdot SiO_2$), ($2CaO \cdot Al_2O_3 \cdot SiO_2$); while the compositions corresponding to T (or any point on the line joining the compositions $2CaO \cdot SiO_2$, $2CaO \cdot Al_2O_3 \cdot SiO_2$) behave as binary systems, solidifying to the two phases ($2CaO \cdot SiO_2$), ($2CaO \cdot Al_2O_3 \cdot SiO_2$).

These facts—and indeed the general appearance of the diagram—illustrate the complications likely to be encountered in relatively simple systems, and show that for systems of from four to eight or more components appearances afford a plain warning against hasty generalization, even if initial homogeneity of material and the continuous attainment of equilibrium could be assumed.

The ternary system $CaCl_2$-$MgCl_2$-H_2O.—This system, which was very carefully investigated by Van't Hoff, Kendrick, and Dawson,[1] is an example of a system with a variable phase (solution). The determination of the quintuple point of such a system will always be a matter of great difficulty, since in this case pressure, temperature and concentration (composition of the variable phase) are all fixed.

[1] *Z. physik. Chem.*, XXXIX (1902), 27.

At 1 atm. and 21°.95 there is equilibrium between the four phases ($MgCl_2 \cdot 6H_2O$), ($CaCl_2 \cdot 6H_2O$), ($CaCl_2$, $2MgCl_2$, $12H_2O$),[1] and solution, the composition of which is $100H_2O$, $4.92MgCl_2$, $9.27CaCl_2$. The reaction may therefore be written as follows:

$$\underset{\text{Solid}}{1\,(MgCl_2 \cdot 6H_2O)} + \underset{\text{Solid}}{1.188\,(CaCl_2 \cdot 6H_2O)} = \underset{\text{Solid}}{0.252\,(CaCl_2 \cdot 2MgCl_2 \cdot 12H_2O)} +$$
$$\underset{\text{Solution}}{0.101\,(100H_2O,\ 4.92MgCl_2,\ 9.27CaCl_2)}$$

A *C* *B* *L*

Now if the temperature is changed, the pressure remaining constant, one of the above 4 phases must disappear; and it has been found that the right-hand side is favored by increase of temperature. Therefore at temperatures below 21°.95 and 1 atm. there can coexist: either

$$(MgCl_2 \cdot 6H_2O),\ (CaCl_2 \cdot 6H_2O),\ \text{solution} \qquad (1)$$

or

$$(MgCl_2 \cdot 6H_2O),\ (CaCl_2 \cdot 6H_2O),\ (CaCl_2 \cdot 2MgCl_2 \cdot 12H_2O) \qquad (11)$$

while at higher temperatures the possible stable configurations are either

$$(CaCl_2 \cdot 2MgCl_2 \cdot 12H_2O),\ \text{solution},\ (CaCl_2 \cdot 6H_2O) \qquad (III)$$

or

$$(CaCl_2 \cdot 2MgCl_2 \cdot 12H_2O),\ \text{solution},\ (MgCl_2 \cdot 6H_2O) \qquad (IV)$$

The solution has a definite composition corresponding to each temperature. For instance, at 16°.7 in contact with ($MgCl_2 \cdot 6H_2O$) and ($CaCl_2 \cdot 6H_2O$) its composition is $100H_2O$, $6.69CaCl_2$, 5.94 $MgCl_2$; while at 28°.2, in contact with ($CaCl_2 \cdot 2MgCl_2 \cdot 12H_2O$) and ($MgCl_2 \cdot 6H_2O$), it is $100H_2O$, $8.84CaCl_2$, $5.37MgCl_2$.

From this it is evident that not all the systems whose composition can be expressed in terms of $MgCl_2 \cdot 6H_2O$, $CaCl_2 \cdot 6H_2O$ and H_2O can give the 3-phase combinations I, II below 21°.95, or III, IV at temperatures above 21°.95. This may be illustrated by the isotherm for 23° (and 1 atm.), which has the general form given in Fig. 2. *PQ* is the solubility curve of *A*, *QR* that of *B* (tachhydrite), and *RS* that of *C*. The point *Q* gives the composition of the solution in equilibrium at 23° with *A* and *B*; *R*, of that in equilibrium

[1] The so-called tachhydrite.

with *B* and *C*. The combination (*A B*, solution *Q*) can result only when the gross composition is within the triangle *ABQ;* the combination (*B C*, solution *R*), only when the composition falls within *BCR*. The triangles *APQ*, *BQR*, and *CRS* are the regions in which the two-phase combinations of solutions with *A*, *B*, or *C*, respectively, are stable.

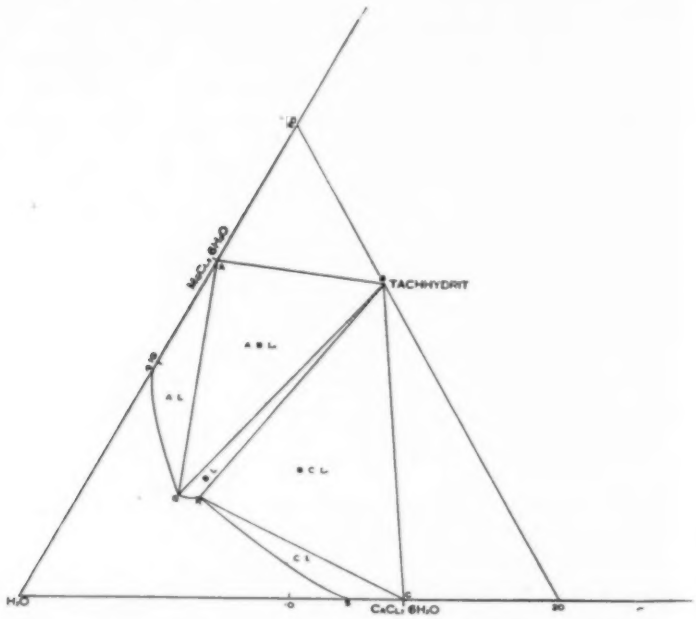


FIG. 2.—Portion of diagram for the ternary system H_2O—$MgCl_2$–$CaCl_2$, representing schematically the solubility isotherms at 23° under a pressure of 1 atm.

If, starting from the equilibrium *ACBL* at 21°.95, we raise the temperature by 0°.2, we must raise the pressure by 11.8 atm. in order to prevent the disappearance of any of the four phases; this relation was experimentally determined, so that the direction of this particular 4-phase line at 22° is known. Investigation of the combination *BCL* at higher temperatures (at 1 atm.) showed that at 25° a second 4-phase line is met; at this temperature

therefore, we have in equilibrium *BCDL*, where *D* stands for the solid phase ($CaCl_2 \cdot 4H_2O$). Thus the reaction ($CaCl_2 \cdot 2MgCl_2 \cdot 12H_2O$) + ($CaCl_2 \cdot 6H_2O$) = ($CaCl_2 \cdot 4H_2O$) + solution now takes place, and instead of III (*BCL*) we then have the combinations *DLC* or *DLB*. For instance, at 28°2 ($CaCl_2 \cdot 4H_2O$) and ($CaCl_2 \cdot 6H_2O$) are in equilibrium with solution of the composition $100H_2O$, 14.4 $CaCl_2$, 1.37$MgCl_2$. The relation between *P* and *T* for the 4-phase equilibrium *CDBL* is not known; but by analogy we may consider that its general course is similar to that of the curve for *ACBL*.

All of these relations are exhibited in the subjoined figure (Fig. 3), which represents a part of the ideal figure. From it we see again how relatively small temperature changes and large pressure changes alter the type of the 3-phase, and also of the 2-phase, combinations.

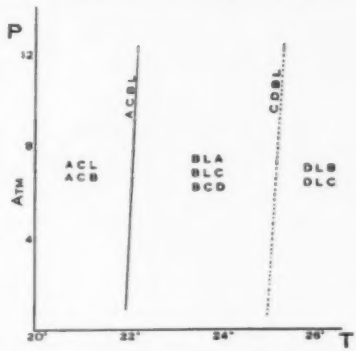


FIG. 3.—Portion of *PT* projection for system $H_2O \cdot MgCl_2 \cdot CaCl_2$, representing the stable 3-phase groupings and two 4-phase lines.

Consideration of an ideal case.—Let us suppose that between the four minerals *ABCD*, whose compositions may be expressed in terms of the three components *K*, *L*, and *M*, the relation $n_1A + n_2B \rightleftharpoons n_3C + n_4D$ exists;[1] it being assumed further that there are no false equilibria or unstable combinations. At arbitrary pressure and temperature only three of these can coexist; let the right-hand side be favored by lowering of temperature and of pressure. Then at low temperatures and small pressure, we should have the stable combinations *ABC* or *ABD;* at high temperatures and pressures, *CDA* or *CDB*.

[1] This equation is analogous to the equation already given for the system $CaCl_2 \cdot MgCl_2 \cdot H_2O$. The complete analytical presentation of the relations for ternary systems is given by Schreinemakers in *Heterogene Gleichgewichte*, III, 210 f., which the reader desirous of fuller information with regard to ideal cases is advised to consult. (This book forms the third volume of the treatise, of which Vols. I and II only were completed by Roozeboom.)

Let us assume further that the minerals X, Y, Z are stable both above and below this inversion point, that they are made up of other components and do not affect the equilibrium relations of $ABCD$. We could then have the rocks $XYZABC$ (I), $XYZABD$ (II) on the one hand, $XYZCDA$ (III), $XYZCDB$ (IV) on the other. These four types are the ideal ones in the temperature, pressure and concentration region characterized by the relation $n_1A+n_2B \leftrightharpoons n_3C+n_4D$. Now if a rock of type I comes into the temperature and pressure regions of types II or III, then D must be formed and either A or B must disappear.

Now the relations in actual metamorphic processes are complicated by a number of factors: that the rate of reaction is often small, that metastable forms occur, or that false or partial equilibrium only is attained. Hence we cannot know if a relation observed in the study of thin sections of a series of rocks is really characteristic of the temperature and pressure conditions which obtained during the process of metamorphism. Nevertheless, although the whole transformation may be metastable, it may be profitable to consider the ideal relation involved.

On the other hand, the formation of a variety of combinations is favored by the circumstance that pressure and temperature change during the metamorphic process and that the co-ordinates of the invariant point of neighboring and chemically very similar rocks may be different. Indeed in geologic units one seldom finds the production by metamorphism of a single type of mineral composition; instead of this there is usually a whole series, the individual members of which are closely interrelated. To take a few examples which have been investigated, there are: the hornblende porphyroblastic schists of Tremola[1] (Gotthard, Switzerland); the glaucophane schists of Syra[2] (Greece) and of the Val de Bagne[3] (Wallis, Switzerland); the chloritoid schists of the Garvera[4] region (Gotthard); the eclogites of the Ötztal[5] (Tyrol), etc.

[1] L. Hezner, *Neues Jahrbuch f. Min.*, Beilage Band XXVIII (1908), 157.

[2] H. S. Washington, *Am. Jour. Sci.* (4), XI (1901), 35.

[3] T. Woyno, *Neues Jahrbuch f. Min.*, Beilage Band XXXIII (1911), 136.

[4] P. Niggli, *Beiträge geol. Karte Schweiz*, N.F., XXXVI (1912).

[5] L. Hezner, *Tsch. Min. Petr. Mitteil*, XXII (1903), 437, 505.

In concluding this section we wish to state again our precise standpoint with reference to the application of the phase rule. To say that the phase rule must always hold for metamorphic systems is equivalent to the assumption that such systems always attained a state of equilibrium; which is certainly not true. Many rocks will be found to contain a larger number of minerals than the maximum number required by the phase rule. On the other hand, the fact that the number of minerals found agrees with this maximum is absolutely no criterion of the attainment of a state of stable equilibrium within the system; for at equilibrium there will in many cases be present fewer phases than this maximum number. One may say only that the rocks will show a tendency toward equilibrium, that they will tend to attain the state corresponding to the ideal *PT* diagram; the ideal types therefore are to be considered merely as representative examples which also will be of use in classifying actual rocks.

Consideration of ideal types may also be of great advantage in classifying metamorphic rocks; just as in the classification of crystals the ideal crystal form is used, although it is seldom that two crystals of the same substance separate out in precisely identical form. As an instance of its use in this way we may recall the well-known work of V. M. Goldschmidt on the contact rocks of the Christiania region.

The foregoing treatment applies only to cases where the metamorphic process has not been accompanied by any change in the gross composition of the material; the question of what happens in such case is taken up later. Here we will remark only that it is by no means necessary that rocks which *now* show identical chemical compositions should be made up of the same mineral constituents; for the reason that differences, and comparatively slight differences, in the amounts of volatile components ("mineralizers") *originally* present might easily alter the character, and order of separation, of the minerals formed in the metamorphic process.

THE GENERAL EFFECTS OF NON-UNIFORM COMPRESSION

The effects produced by exposure to non-uniform compression are in general permanent; that is, the original state of the system

is not re-established when the compression ceases. The effect of differential compression may be resolved into two parts: that due to a (smaller) uniform pressure and that due to a shearing stress, the latter being the preponderating effect. The mere fact that "flow" or deformation of the compressed material occurred is sufficient evidence that unequal stresses were set up; in other terms, that the compression was not uniform. In discussing this question it will be convenient to treat first the effects of stress on a solid phase alone before passing on to the consideration of systems solid-liquid or of those in which we may imagine the appearance of a liquid phase to be one of the results of stressing the solid phase; the latter is much more fundamentally important in relation to metamorphic processes than the former.

The effects of stress on the solid phase alone.—The effects of stress on solids are what we are accustomed to call mechanical; they are subsidiary, rather than essential, in metamorphic processes. For this reason, and because the general subject has been discussed by Willard Gibbs, while its geological applications form the subject of a number of well-known papers,[1] the effects of stress on solids will be treated very briefly here.

Any directed stress acting on a particle may be resolved into three stresses, each acting on an element of surface in one of the three principal planes. These three stresses are represented both in direction and intensity by the three principal axes of an ellipsoid. The stress produces in the particle a strain, which will tend to change the shape of the particle, or its size, or both together. At any point there will be three mutually perpendicular directions in which the displacement is a maximum or minimum and about which these displacements will be symmetrically arranged as an ellipsoid is about its three axes. A homogeneous isotropic sphere exposed to the action of a stress will assume the form of the so-called strain-

[1] C. R. Van Hise, "Metamorphism of Rock and Rock Flowage," *Bull. Geol. Soc. Am.*, IX (1898), 269; G. F. Becker, "Finite Homogeneous Strain Flow and Rupture of Rocks," *Bull. Geol. Soc. Am.*, IV (1893), 13; "Schistosity and Slaty Cleavage," *Jour. Geol.*, IV (1896), 429; "Experiments on Schistosity and Slaty Cleavage," *Bull. U.S. Geol. Survey 241* (1904); C. K. Leith, "Rock Cleavage," *Bull. U.S. Geol. Survey 239* (1903); L. M. Hoskin in *16th Annual Report, U.S.G.S.*, Part I, 1896; P. Niggli, *Beiträge geol. Karte der Schweiz*, N.F., XXXVI (1912).

ellipsoid, the position of which, and thus the state of strain, at any point is completely determined.

The strain- and stress-ellipsoids are parallel to one another only in isotropic media, and then only when the stress acts continuously in a definite direction. The presence of particles of unequal hardness —in other words, heterogeneity of the material—results obviously in the cessation of this parallelism. The position of the strain-ellipsoid is influenced by the exact distribution of the particles of unequal hardness; and, on the other hand, the position of these fine layers—in so far as it can change at all—is determined by the direction of the strain-ellipsoid (tectonic displacements). The orientation of newly formed mineral grains is determined in general by the relations of stress and strain, the most thorough adaptation being attained when flow cleavage takes place. In the crystalline schists formed under stress which show heteroblastic structure the orientation of the porphyroblasts is indefinite, which is presumably due to their rate of formation. That their orientation does not correspond to the conditions of strain is evident from the fact that subsequent rotational movements have sometimes occurred,[1] accompanied by cataclastic phenomena. Cataclastic effects predominate in the so-called mylonitized rocks, which are found principally where thrusting has taken place.

The optical properties of crystals are influenced by stress. Isotropic minerals may become biaxial, if the direction of the principal stress does not correspond with that of the axes of symmetry. Uniaxial crystals become optically biaxial when the direction of the stress is other than that of the optic axis of the crystal; for instance, in crystalline schists quartz occurs frequently as optically biaxial crystals, which at the same time show elliptical, in place of circular, polarization, and undulatory instead of definite extinction. Application of stress changes in general the position of the principal axes of biaxial crystals; when the stress-ellipsoid is parallel to the ellipsoid derived from the crystalline axes there will be a change only in the refractive indices and in the optic axial angle.

Furthermore, stress may to some extent produce gliding or translational displacements in the individual mineral grains. As

[1] P. Niggli, *Beiträge geol. Karte Schweiz*, XXXVI (1912), 61.

instances of the phenomena of gliding, calcite frequently is found twinned in the $(10\bar{1}2)$ plane; diallage also frequently exhibits lamellae which have resulted from stress. Translational displacements are those in which the displaced portion remains parallel to its original position; this phenomenon is shown—though usually only to a small extent—by plastic crystals, such as cyanite, augite, mica, graphite, calcite, brucite, when they occur in metamorphic rocks.[1]

On the other hand, many crystals found in crystalline schists are the net result of a more or less thoroughgoing destruction of the original configuration of the system and of more or less shattering of the individual crystals, followed by a healing-up of the cracks and spaces thus produced. To account for this we are led to consider the effect of stress on the processes of fusion and solution.

Effects of stress on systems solid-liquid.—It has been shown in two previous papers[2] (to which the reader desirous of a fuller discussion of this topic is referred) that the observed effects of non-uniform compression can be satisfactorily correlated by ascribing them to the action of "unequal" pressure, that is, to a pressure which, in a system solid-liquid, acts on the solid phase but not, or not to the same extent, on the liquid phase. It can readily be shown from thermodynamic reasoning that the effect of unequal pressure is *always* to lower the melting point (or raise the vapor pressure, and hence the solubility) of a substance, and by an amount which is many times as great as the effect (raising or lowering) produced by the same pressure acting on both phases simultaneously.

The principle that unequal pressure lowers the melting-point was formulated first in 1881 by Poynting,[3] who applied it only to calculate the effect on the melting-point of ice. In 1892 the result was stated by Le Chatelier,[4] who applied it to several problems of

[1] See papers by O. Mügge, e.g., *Neues Jahrbuch f. Min.*, I (1898), 71; II (1899), 55; also L. Milch, *ibid.*, I (1909), 60.

[2] J. Johnston, *Jour. Am. Chem. Soc.*, XXXIV (1912), 788; *Z. anorg. Chem.*, LXXVI (1912), 361; J. Johnston and L. H. Adams, *Am. Jour. Sci.*, XXXV (1913), 205; *Z. anorg. Chem.*, LXXX (1913), 281.

[3] *Phil. Mag.* (5), XII (1881), 32.

[4] *Z. physik Chem.*, IX (1892), 335.

geological interest—to the regelation of ice and the consolidation of beds of gypsum.

In a paper[1] first published in 1894, E. Riecke discussed the effect of a one-sided pressure (a stress) on the melting-point of ice, and quite recently he has restated his conclusions in a second paper.[2] Riecke's formula for the lowering of melting-point of ice effected by the stress Z (tensile or compressive) is

$$\Delta T_1 = -aZ^2$$

where (for ice) a has the value 0.00036 when Z is expressed in kg. per sq. cm.[3] He appears to consider this formula, which was developed for the case of a single crystal only, valid only for small values of Z; so that its range of applicability is somewhat limited. It has, under the name of the Riecke principle, been adduced occasionally by geologists[4] to aid in correlating observations connected with metamorphic processes and results.

The basic principle underlying Riecke's reasoning is identical with that used in the derivation of the equation used in the present paper, which, as mentioned above, was derived first by Poynting; but the latter, which is derived from general thermodynamic principles without specific assumptions (other than those common to all thermodynamic reasoning), is much more generally applicable, holding as it does for solid aggregates, and for any range of pressures, subject always of course to the condition that the pressure acts on the solid phase, but not, or to a less extent, on the liquid phase produced by melting or by solution.

Derivation of the formula: The derivation of the formula by means of which the effect of unequal pressure on a substance is computed is based on the thermodynamical fact that unequal pressure acting on any phase increases the "activity" of that phase, or its tendency to pass over into another phase; in other terms, unequal pressure acting only on the solid phase increases its vapor pressure and its solubility (in any particular solvent) and lowers

[1] *Nachr. Ges. Wiss. Göttingen*, 1894, 278; *Ann. Physik*, LIV (1895), 731.

[2] *Centralblatt Min. Geol.*, 1912, p. 97.

[3] 1 atmosphere = 1.033 kg. per sq. cm.

[4] For instance by Grubenmann, *Die kristallinen Schiefer*, 2 Aufl. (1910), and by Becke, *Denkschriften Wien Akad.*, 7 Mai, 1903.

its melting-point. Into the steps in the derivation of this formula it is unnecessary to enter here;[1] the final differential equation is:

$$\frac{dT}{dP}=\frac{TV_s}{\Delta H} \qquad \text{(V)}$$

which expresses the lowering of melting-point by unequal pressure in terms of the absolute melting-point (T) and the molecular volume (V_s) of the solid at the temperature and pressure in question and ΔH, the molar heat of fusion under those conditions. The quantities V_s and T are always positive, but ΔH (as here used) is always negative; hence application of excess pressure on the solid phase *always* lowers the melting-point.

If we compare the melting-point depressions (dT_1 and dT_2 respectively) produced by the same excess pressure (dP) acting on (1) the solid phase alone, (2) both phases; that is, if we combine equations V and I, we obtain the result

$$\frac{dT_1}{dT_2}=\frac{V_s}{dV}=\frac{V_s}{V_s-V_l} \qquad \text{(VI)}$$

or, expressed in words, the ratio of the lowering of melting-point of the solid phase, when this alone is subject to a given pressure, to the alteration (raising or lowering) observed with the same (given) pressure acting uniformly on both phases is equal to the ratio of the (specific) volume of the solid phase to the change of (specific) volume on freezing.

This equation shows how many times greater the melting-point lowering is when the pressure acts only on the solid phase. For example, the melting-point of ice is lowered by unequal pressure 12 times as much (or 0°.09 per atm.) as by uniform pressure (0°.0075 per atm.); in general $\Delta T_1/\Delta T_2$ is much greater than 12, because the fractional change of volume accompanying melting is usually much smaller than it is in the exceptional case of ice.

The (unequal) pressure (ϕ, expressed in atmospheres) required to cause a substance to melt at the temperature T_2 can be computed if we can integrate equation V. We cannot perform this integration rigidly for lack of the necessary data on the variation of

[1] It is discussed in another paper: see *Jour. Am. Chem. Soc.*, XXXIV (1912), 788-802; *Z. anorg. Chem.*, LXXVI (1912), 361-79.

ΔH and V_s with pressure and temperature; but fortunately the variation of $V_s/\Delta H$ is small and for the present purpose unimportant. We may therefore consider $V_s/\Delta H$ to be independent of pressure and temperature; by integration and transformation we then obtain the equation

$$\phi = 95.1\, QD \log \frac{T_1}{T_2} \qquad \text{(VII)}$$

which gives the unequal melting-pressure (ϕ) at the temperature T_2 in terms of the heat of melting (Q, in calories per gram), the density D, and the ordinary melting-point at 1 atm. pressure (T_1, in absolute measure). At the present time the data requisite for the

TABLE III

LOWERING OF MELTING-POINT OF METALS EFFECTED BY ONE ATM. UNEQUAL PRESSURE; TOGETHER WITH THE COMPUTED MELTING-PRESSURES (IN ATM.) AT ORDINARY TEMPERATURES

METAL	MELTING-POINT		HEAT OF FUSION Q	DENSITY D	ΔT_1	ϕ_{27}
	t	T_1				
K	62	335	15.7	0.87	0.59	64
Na	97	370	31.7	0.98	.29	266
Pb	327	600	5.4	11.37	.24	1,760
Sn	232	505	14.1	7.29	.12	2,200
Bi	270	543	12.5	9.80	.11	3,000
Cd	321	594	13.7	8.64	.12	3,300
Al	658	931	42.0	2.60	.21	5,100
Zn	419	692	28.0	7.1	.084	6,900
Ag	960	1,233	23.0	10.50	.12	14,000
Cu	1,083	1,356	43.0	8.93	.086	24,000
Pd	1,550	1,823	36.3	11.4	.11	31,000
Pt	1,755	2,028	27.2	21.5	0.084	46,000

calculation of ϕ are available only for a few metals; these calculations have been made and the results are presented in Table III; the sixth column (headed ΔT_1) gives the melting-point depression[1] produced by 1 atm. excess pressure acting on the solid, the last (headed ϕ_{27}) contains the computed pressure (in atmospheres) which, acting on the solid alone, would be required to cause the substance to melt at 27°.

[1] As calculated by the formula $\Delta T_1 = \dfrac{T_1}{41.30\, QD}$, which is easily derived from equation V.

By comparison of the above results with those of Table I we see how much greater the effect of unequal pressure may be. For example, take the case of lead, the melting-point of which is changed +0°.008 by 1 atm. uniform pressure, but −0°.24, or 30 times as much, by 1 atm. excess pressure on the solid phase.

The sequence of the metals when arranged in the order of their ϕ values (as computed from equation VII) is identical with that obtained when they are arranged in the order of their flow pressures or of any of their elastic properties (e.g., tensile strength, hardness). This parallelism is a striking corroboration of the effectiveness of unequal pressure in correlating phenomena attending the deformation of crystalline solids.[1]

It is of interest to inquire if there is any relation between the hardness of minerals and any of their other properties. There is a parallelism between the hardness of the metals (as ordinarily measured) and the calculated ϕ values, which depend upon the density, heat of melting, and temperature of melting. Of these three factors the first lies within comparatively narrow limits for a series of minerals; the second is not known, but probably lies also between comparatively narrow limits *in general;*[2] the limits within which the melting-point lies are comparatively much wider apart. Consequently, we should expect that there is a rough parallelism between the hardness of minerals and their melting-point.

That this expectation is justified is shown by Fig. 4, in which the melting-point of those minerals which give congruent melting-points is plotted against the hardness; this has been done for all minerals for which the necessary data could be found in Landolt-Börnstein *Tabellen*. All of the points lie within a zone the breadth of which is no greater than one might expect from the very uncertain nature of the measurements of hardness, and in view of the circumstance that the latent heat has not been taken into account. When the latent heat is taken into account (which is possible only for a few of the metals) and the ϕ values plotted against hardness the

[1] For a discussion of this question see Johnston, *Jour. Am. Chem. Soc.*, XXXIV (1912), 788; *Z. anorg. Chem.*, LXXVI (1912), 361.

[2] The exceptional cases would be those in which the heat of melting is very small.

points lie within a very much narrower zone. From this we can infer that the same will be found for the minerals when the requisite data are known.

There is therefore a considerable body of evidence then which suggests that any permanent deformation of a crystalline dry aggregate is determined by an actual melting of some part of the material—a melting which occurs as soon as the local stress reaches the melting-pressure corresponding to the temperature of the material—with subsequent resolidification; this resolidification consists in the production of crystals of that form which appears

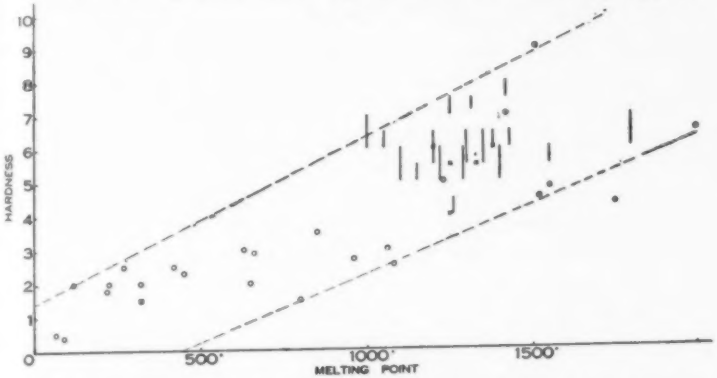


FIG. 4.—Diagram to exhibit the relation between hardness (as ordinarily measured) and melting-point. Circles represent elements; crosses or lines represent minerals, lines being used where the tables give a value such as 5.5—6.5.

most readily under the particular conditions of pressure (and therefore not necessarily of the original form) and, so far as the argument is concerned, recrystallization need not be complete. So far as we are aware, there is no evidence which directly contradicts the above hypothesis; on the contrary this hypothesis enables us to correlate and interpret a large number of diverse and apparently contradictory observations.[1]

This type of compression accounts easily for regelation; the most common example is the regelation of the substance water which, as it happens, is exceptional in that its freezing-point is

[1] See Johnston and Adams, *Am. Jour. Sci.*, XXXV (1913), 205.

lowered by uniform pressure. This phenomenon cannot in general be produced by uniform pressure because uniform pressure raises the melting-point of most substances; so that we shall with advantage consider unequal pressure to be the effective factor in the case of water as in that of other substances. Consider a block of ice at 0° supporting a loaded wire. The pressure exerted by the wire depresses the melting-point of the ice by an amount Δt; immediately beneath the wire, therefore, we have at any instant a thin layer of ice at $-\Delta t$ in equilibrium with water at $-\Delta t$. The water, however, escapes round the wire, and so comes into contact with ice at 0°; such a system is, however, unstable, for under these conditions water cannot remain subcooled. Consequently, the water freezes again and forms a solid block above the wire.

The process by which a mass of loose snow is compacted into a block of ice is identical with this. The pressure, due to the superincumbent material, lowers the melting-point at the surface of contact of adjacent grains; the water at $-\Delta t$ flows into the interstices where the pressure is smaller and freezes again. This process continues until the interstices are all filled up, that is, until a solid block of ice is formed. This again, we believe, is the general mode in which consolidation of a mass of originally loose material takes place, as for instance in the welding of metals and in pyrometamorphic processes. The consolidation of loose mineral material, however, takes place more usually through a process of solution, the general principle being identical in both cases; this we shall now consider.

Influence of unequal pressure upon the solubility of solid substances.—Considerations in every respect analogous to the foregoing are applicable to systems of a solid in contact with water or other solvent; in such cases, pressure acting in excess on the solid increases its solubility,[1] and thus renders the solutions supersaturated with respect to the *unstressed* solid. Le Chatelier[2] accounts in this way for the consolidation of natural beds of rock-salt, gypsum, calcium carbonate, and clay. To test this matter directly he

[1] The amount of this increase of solubility can be computed from equations analogous to those applicable to melting-points.

[2] *Z. physik. Chem.*, IX (1892), 335.

compressed sodium chloride or sodium nitrate in contact with its saturated solution to about 200 atmospheres for a period of eight days, and found that blocks resembling rock-salt and marble were formed in this way. Similarly one can account for the formation of rigid sandstones from beds of originally loose sand.

Application to metamorphic processes.—The processes just discussed have a very important bearing on rock metamorphism wherever stress has been an important factor. The unequal pressure increases the activity of the solid components, and fusion or solution occurs wherever the local stress reaches the appropriate value. In this way larger amounts of material come into local solution to be immediately redeposited (at points where the stress is smaller) in the form characteristic of those particular conditions, and hence not necessarily in the original form; consequently reactions occur more readily in stressed rocks. The nature and form of the new crystals depend therefore upon the relations of stress and strain in the mass. The so-called Riecke principle has been adduced in this connection; but the whole question has been handled in a much more general way by Willard Gibbs,[1] from whom we quote the following sentences:

> If a solid which is homogeneous in nature and in state of strain is bounded by six surfaces perpendicular to the principal axes of stress, the mechanical conditions of equilibrium for these surfaces may be satisfied by the contact of fluids having the proper pressures, which will in general be different for the different pairs of opposite sides, and may be denoted by p', p'', p'''. It will then be necessary for equilibrium with respect to the tendency of the solid to dissolve that the potential for the substance of the solid in the fluids shall have certain values μ', μ'', μ''', which are entirely determined by the nature and state of the solid.

From Gibbs' equations it follows directly that μ' is "greater than the value of the potential which would be necessary if the solid were subjected to the uniform pressure p'" (and similarly with μ'', p'', μ''', p''').

> That is, the fluids in equilibrium with the solid are all supersaturated with respect to the substance of the solid, except when the solid is in a state of hydrostatic stress [uniform pressure]; so that if there were present in any one of

[1] "Equilibrium of Heterogeneous Substances," *Collected Papers*, pp. 196–97. The question was first treated by James Thomson, *Trans. Roy. Soc. Edinburgh*, XVI, 575; *Proc. Roy. Soc.*, XI, 473; *Phil. Mag.* (4), XXIV, 395.

these fluids any small fragment of the same kind subject to the hydrostatic pressure of the fluid, such a fragment would tend to increase. Even when no such fragment is present. . . . . the presence of the solid which is subject to the distorting stresses will doubtless facilitate the commencement of a solid of hydrostatic stress upon its surface. . . . . But in the case of a solid of continuous crystalline structure, subjected to distorting stresses and in contact with solutions satisfying the conditions deduced above . . . . within certain limits the relations given must admit of realization, especially when the solutions are such as can be easily supersaturated.[1]

In other words, when a crystal is strained, the solubility on the strained face is increased. Consequently material tends to dissolve off the strained faces of a crystal in contact with a saturated solution in any solvent, and to be redeposited where the strain is less.[2] The effect of this is that the crystal changes in such a way as to diminish the stress upon it—an example of the well-known principle that the readjustment of a system following disturbance of equilibrium is always such as to minimize the effect of the disturbing factor.

In order to illustrate how stress affects crystallization let us suppose an isotropic sphere exposed to stress. The stress may be resolved into three stresses acting along axes mutually perpendicular; the sphere is thereby deformed into an ellipsoid, the axes of which in the simplest case coincide with those of the stress-ellipsoid. The final effect is the same when the substance is immersed in a solvent medium, for the solubility is increased most in a plane perpendicular to the greatest stress.

Let us consider now the growth under stress of new isotropic particles. The stress would tend to make the particle ellipsoidal, even though it were to make equal growth in all directions. But the saturation limit is reached soonest in the plane perpendicular to the smallest stress, so that the isotropic particle in growing assumes of itself the form of the strain-ellipsoid. From this it follows that particles growing in a stressed medium will be flattened in a direction perpendicular to the greatest stress and will be paral-

[1] W. Gibbs, *loc. cit.*

[2] This does not necessarily imply that the material be redeposited on the unstrained faces of the original crystals; it may go to form new individuals. In very many cases, of course, a reaction or transformation will occur, so that the material will not be redeposited in its original form.

lel to one another; their arrangement thus corresponds exactly to flow cleavage.

The anisotropic character of minerals (also with respect to their solubility relations) introduces a complication, without, however, affecting the general principle involved. A definite arrangement of minerals with respect to a single vectorial property is often found; such an arrangement can of course only be ascribed to the vectorial properties themselves, whether they be differences in solubility or in cohesion.

In metamorphic rocks exhibiting flow cleavage the flakes of mica lie in such a way that the smallest growth was perpendicular to the base, the greatest growth in the basal (and cleavage) plane. We must remember that the immediate influence of stress and strain is made evident in an unequal development in different directions, although the general principle alone gives us no information as to the particular vectorial direction which is parallel to the smallest development. But when we take into account the anisotropy exhibited by the original tiny particles, we must include as one of the factors the orientation of the original particles with respect to certain directions within the crystal; those directions, namely, parallel to the plane (gliding plane) in which displacement of the crystal particles is most readily effected, and perpendicular to the plane (cleavage plane) in which the crystal most readily splits. When the rates of growth or the solubility relations are anisotropic, specific effects analogous to the above will be produced; but of this influence little that is definite can at present be said except that it certainly is appreciable.

From this it follows that the relicts will tend to assume the form of the strain-ellipsoid (if we neglect for the moment the complications introduced by anisotropy). And indeed it is well known that the quartz relicts in rocks originally conglomerate are more or less oval in form. Further, the recrystallization will tend to take place in such a way that the strain is a minimum. This is the basic principle underlying the phenomenon of flow cleavage; for it corresponds to minimum expenditure of work in producing the new formation, or in other words it represents the most complete adaptation of the system to the strains acting upon it.[1] The

[1] P. Niggli, *Beiträge geol. Karte Schweiz*, N.F., XXXVI (1912), 46.

flow of rocks has been studied experimentally, notably by F. D. Adams and his collaborators;[1] it resulted always in the production of a kind of cleavage.

It is characteristic of those cases of metamorphism where stress has been the predominant factor that the system, taken as a whole, is not in simple equilibrium, but rather in a stationary condition only. Now since, as we have seen, unequal stress acts mainly by depressing the melting-point and by raising the solubility, it follows that its effect on the transformation solid-solid is very small. Consequently we might expect that the forms produced under unequal stress would often be forms which cannot be obtained from ordinary melts; and this indeed is often observed.

Let us compare the mineral composition of the crystalline schists (which have very often been formed under stress) with that of eruptive rocks or with metamorphic rocks of the Katazone, making use of the summary given by Grubenmann[2] (see p. 613).

From this summary it is evident that many of the minerals occurring in rocks which have been subjected to unequal stress occur also as ordinary products of the secular alteration of magmatic minerals at low temperatures. The water content of many of them determines in large part their behavior when heated or melted under ordinary conditions. Nevertheless the paragenesis of the stress minerals is, as Grubenmann has pointed out, characteristic of relatively low temperatures. Stress has increased the "activity," so that in stressed systems some reactions readily take place which otherwise would go very slowly. Thus unequal stress may be regarded as a kind of catalytic agent, though in thinking of it in this way one must remember that it has frequently a characteristic influence on the nature of the products of a reaction, in addition to its influence on the rate of formation of those products.

In spite of the fact that in stressed systems we are not dealing with simple equilibrium conditions, we may apply principles similar to those set forth on p. 597 to ideal typical systems. In doing

[1] *Phil. Trans. Roy. Soc. London*, A, CXCV, 363; *Am. Jour. Sci.*, XXIX (1910), 465; *Jour. Geol.*, XVIII (1910), 489; *XI Congrès geol. internationale*, II (1910), 911.

[2] *Die kristallinen Schiefer*, 2. Aufl., 1910.

this we would consider only a simple equilibrium characteristic of relatively low temperatures, remembering always that the conclusions reached by this means are subject to considerable limitation; still such conclusions may be useful for purposes of classification, if for no others.

Main Components	Stress Mineral	Corresponding Minerals in Katamorphic Rocks or in Eruptive Rocks	Products Obtained on Heating or Fusing the Stress Mineral
H_2O, Al_2O_3, K_2O, SiO_2	Sericite	Alkali feldspar, muscovite?	Leucite, nephelitic mineral, glass
H_2O, Al_2O_3, K_2O, MgO, FeO, SiO_2	Biotite	Biotite	Olivine, spinel, leucite(?), glass
H_2O, MgO, FeO, SiO_2	Chlorite	Partly biotite, partly olivine, spinel, augite	Spinel, olivine +?
H_2O, FeO, SiO_2, Al_2O_3	Chloritoid	Cordierite+sillimanite, spinel	.....
H_2O, FeO, Al_2O_3, SiO_2	Staurolite	Same as chloritoid	.....
H_2O, Fe_2O_3, Al_2O_3, CaO, SiO_2	Epidote	Consist of plagioclases in combination with pyroxenes, etc. Epidote is also a primary constituent of some granites	Anorthite and lime-augite
H_2O, Al_2O_3, CaO, SiO_2	Zoisite	Consist of plagioclase	.....
H_2O, CaO, MgO, SiO_2	Nephrite, actinolite	Augite and olivine	.....
H_2O, MgO, FeO, CaO, Al_2O_3 alkalies, SiO_2	Hornblendes	(In part) basaltic hornblendes or pyroxenes	Pyroxene+olivine
Na_2O, Al_2O_3, SiO_2 {FeO / MgO}	Glaucophane	?	?
CaO, MgO, FeO, Al_2O_3, SiO_2	Garnet	Garnet, plagioclase, olivine, pyroxene	Anorthite, monticellite, melilite, olivine, meionite
Al_2O_3, SiO_2	Kyanite (Andalusite)	Sillimanite, andalusite	.....

Influence of stress on reactions accompanied by the production of a vapor phase.—In considering the effects of stress it is absolutely essential to note that the influence of stress on reactions which are accompanied by the evolution of a gas or vapor is enormous. For instance, it is well established that continued grinding in a

mortar of minerals containing water or even of substances containing water of crystallization results in a loss of water;[1] thus apophyllite on grinding lost about 1 per cent of water (Thugutt), $MgSO_4 7H_2O$ lost about 2.5 per cent H_2O (Blecker). Moreover, Johnston has found[2] that some carbon dioxide can be driven off from a substance as stable as calcium carbonate by grinding it in a mortar for a few minutes; in this case the grinding lowers the temperature at which the calcium carbonate exhibits an appreciable pressure of carbon dioxide by some 500°.

This behavior is in thorough accordance with the standpoint adopted with regard to the effects of unequal pressure. Application of precisely similar reasoning leads to a formula entirely analogous to equation V, namely:

$$\frac{dT_p}{dP}=\frac{T_p V}{\Delta H} \qquad (Va)$$

where T_p is the temperature corresponding to a given pressure of the vapor phase, ΔH the heat of reaction, and V a (specific) volume, which practically will be intermediate between that of the original solid and the volume change accompanying the reaction. Furthermore, we see that the unequal pressure required to produce an appreciable pressure (p) of the vapor phase at a given temperature would be approximately proportional to $Q \log T_p$,[3] T_p being the temperature at which the system in the unstressed condition would exhibit the vapor pressure p, and Q the heat of dissociation; and this conclusion is roughly borne out by the observations hitherto recorded.

Analogous considerations apply to reactions such as $RCO_3 + SiO_2 \rightarrow RSiO_3 + CO_2$; the general conclusion being that unequal stress will cause reactions between solids accompanied by the devel-

[1] Mauzelius, *Sveriges Geol. Undersökning Arsbok*, I (1907), No. 3; W. F. Hillebrand, "Influence of Fine Grinding on the Water and Ferrous Iron Content of Minerals and Rocks," *Jour. Am. Chem. Soc.*, XXX (1908), 1120: *Chem. News*, XCVIII (1908), 205, 215, who refers to some earlier observations; S. J. Thugutt, *Centr. Min. Geol.* (1909), p. 677; I. B. Blecker, *Chem. News*, CI (1910), 30.

[2] A separate note dealing with this question is in course of preparation.

[3] Since from one substance to another there is comparatively little variation of V, but large variations of Q and T_p.

opment of a gas phase to proceed to an extent which would be inappreciable in the absence of stress. This renders it evident, as has been noted on a previous page, that great care must be exercised in choosing points for purposes of a geologic thermometer; for the only points really adapted to this purpose are transitions solid-solid (which, moreover, must not be much affected by uniform pressure), while systems in which a vapor phase intervenes are altogether useless for this purpose.

METAMORPHISM ACCOMPANIED BY ADDITION OF MATERIAL

Hitherto we have considered only those cases of metamorphism where there was no addition of material during the process; this limitation permits us to consider the changes produced in a given chemical system by a change in its physical conditions and environment. As a matter of fact, chemical investigation of metamorphic rocks[1] has shown that in many cases the gross composition of the original eruptive or sedimentary rocks has remained sensibly unaltered by the metamorphic processes;[2] in other cases, on the other hand, it has shown that an addition of material did occur during the process of metamorphism.

Now the addition of material, whether temporary or more or less continuous during the process, is often the main cause of the changed physical conditions, therefore the cause of the metamorphic process. When this is so the chances for a complete transformation of the rock are in general more favorable than when temperature and pressure alone are variables. Thus it is that in rocks which have been metamorphosed with, or by, the addition of foreign material there are peculiarities in mineral content and often in texture and structure. In all such cases it is to be noted that the gross composition of the rock *now* can give us no certain idea of the composition of the system during metamorphism, and therefore that two rocks which now have the same bulk composition may then have represented quite different chemical types.

[1] Grubenmann, *Die kristallinen Schiefer*, II. Teil, 2. Aufl., 1910.

[2] The occurrence of small changes of composition, such as have been noted, e.g., by J. D. Trueman (*Jour. Geol.*, XX, 228 f.), is an occasional, but certainly not a general, phenomenon. Such small changes exert no marked specific influence on the general result, and consequently are not specially discussed here.

The term metamorphism with addition of material we reserve for the changes characterized by a penetration of the original rock by some foreign system; we do not use it to denote the small local changes in concentration which may have taken place. The foreign system, the viscosity of which must be comparatively small, will generally be of magmatic origin; we must therefore briefly consider magmatic processes.

Magmas are mixed solutions of silicates, charged with volatile substances, the so-called gas mineralizers, the amount of which, varying with the progress of the intrusion and solidification, depends upon the previous history and original composition of the particular magma basin. Of these volatile components, the majority can exist, *when alone*, only as gases at the temperature at which the magma crystallizes.

Analysis of volcanic exhalations has led to the recognition of the following gases and vapors, excluding those of minor importance: H_2O, H_2, N_2, CO_2, CO, H_2S, SO_2, HCl, Cl_2, CH_4, HF, SiF_4. Which of these appear under given conditions depends mainly upon temperature and pressure, the latter especially, since it influences the equilibrium greatly when the reaction is accompanied by a change in the total number of molecules (especially therefore in cases of dissociation or association). Conversely, reaction will frequently take place in gaseous systems when the pressure changes, therefore in magmatic gases when they escape into a region of lower pressure. Such reactions are often attended by a large evolution of heat, which is doubtless one of the sources of heat, and possibly even one of the causes of volcanic outbreaks. For any reaction which evolves much heat and proceeds very rapidly may be explosive; for instance, hydrogen and oxygen explode when set off by a spark, that is, when the reaction is started at a high temperature (where its rate is very great), the amount of heat evolved by the reaction being sufficient to prevent a lowering of the temperature of the zone reacting at any moment. When one takes into account the reactivity of gases and the dependence of the position of equilibrium at any moment upon the effective temperature and pressure at that time, one is led irresistibly to the view that from the gases found in the exhalations no safe con-

clusion can be drawn as to the nature of the gaseous phase present in the intrusive magma unless the conditions existing there and their influence upon the equilibrium are all known. Nay more, it is to be expected that the exhaled gases do not represent an equilibrium at all, but are actively in the process of reacting.[1]

The magma also contains, in addition to the above gases and vapors, a number of other substances which are volatile at high temperatures, such for example as metallic sulphides, chlorides or fluorides, and compounds containing boron.

It is not at all necessary that the gaseous components, such as H_2O, H_2S, HCl, SO_2, exist as gases in the magma, even when they are present in the free state and not as compounds. For in that case it is their miscibility with the magma—or in other words, their solubility in it under the particular conditions (of which pressure is obviously the most important)—which determines whether they are present in the liquid phase.

The critical temperature, above which a system can exist only as gas, is a function of the chemical composition of the system. A gas when dissolved in a mixture of non-volatile components will exhibit a higher critical temperature than it does in the pure state; such a solution would of course exert in general a considerable gas pressure, which, however, need not be as great as the critical pressure of the volatile component in the pure state.[2] To illustrate: the critical temperature of SO_2 is 157°.5, its critical pressure is 79 atm. Now if 24.7 parts $HgBr_2$ (the melting-point of which is 236°.5) and 75.3 parts SO_2 are heated in a sealed glass tube, the volume of which is so chosen that the pressure will be about 80 atm. at 157°, melting of the $HgBr_2$ takes place at 230°.[3] This lowering of 6°.5, which is due to the taking-up of SO_2 by the

[1] Day and Shepherd, for example (in the course of an investigation as yet unpublished), find that the gases emerging from the volcano Kilauea contain CO, CO_2, S, SO_2, H_2O, H, Cl, and F—a mixture of gases which cannot possibly coexist in equilibrium.

[2] A full discussion of these matters will be found in P. Niggli, *Z. anorg. Chem.*, LXXV, 161; LXXVII (1912), 321; *Central. Min.*, 1912, p. 321; *Geol. Rundschau*, III (1912), 472. The main points, especially in case the volatile component is water, are treated by Morey and Niggli, *Jour. Am. Chem. Soc.*, XXXV (1913), 1086 f.

[3] *Z. anorg. Chem.*, LXXII (1912), 161 f.

melt, shows that at a pressure of about 100 atm. a considerable quantity of SO_2 is condensed or dissolved in a melt of $HgBr_2$ at 230°, in spite of the fact that the critical temperature of pure SO_2 is 157°.5.

In precisely the same way we can have at high pressures water, or any of the other gases, present in the magmatic melt, and at the same time lowering its melting-point considerably below what it would be were no volatile components present.[1] Initially the amount of volatile component might be small, but its proportion in the liquid would increase (if the pressure remained constant, i.e., unless gas can escape) as crystallization progressed, unless the gas itself entered largely into the solid minerals.

On the other hand, gaseous material at high pressures and at temperatures above the critical can exert some degree of solvent action, as is evident from the following reasoning. The volatile component *A* as liquid can dissolve the non-volatile component *B*. Now unless the solubility of *B* in liquid *A* diminishes very rapidly near the critical point, there will be at that point a definite amount of *B* in solution. But since at the critical point the liquid and gaseous phases are by definition identical, there must then be the same proportion of *B* in the gaseous phase; so that above the critical temperature we can have a gaseous, or better a fluid, solution of a non-volatile substance. In general there is a very marked falling-off in solubility just below the critical point, but this in itself is no reason why at still higher temperatures and pressures the solubility of *B* in *A* should not again increase.

For instance, in fluid SO_2 at 159°.4 and at a pressure of about 80 atm. the solubilities of $HgBr_2$ and HgI_2 are respectively about 1.5 per cent and 0.7 per cent by weight. At 230° in the same volume (hence at correspondingly higher pressures) the amount of $HgBr_2$ dissolved is about 8.5 per cent, while at 254° about 6.2 per cent HgI_2 dissolves in the fluid phase. This example illustrates only the possibility of the phenomenon; the quantitative results cannot of course be transferred to magmatic systems. But the two cases are entirely analogous in principle, and the residual phase from solidification of the magma, even though it be gaseous, is to be looked upon as a solution.

[1] Direct evidence bearing on this point will be presented in the near future.

Under magmatic conditions the volatile substances (such as H_2O, SO_2, CO_2, etc., all of which are to be treated in exactly the same way) may in part unite with some of the other constituents to form more or less stable compounds which may be liquid under the conditions of temperature and pressure obtaining. The proportion combined in this way is controlled by temperature and pressure, the effect of the latter being to raise the concentration in the gas phase and hence, in accordance with Henry's law, in the liquid phase also. An idea of the influence of temperature is afforded by the following recently obtained results: in a melt of 1 mol. K_2O and 0.94 mol. SiO_2 heated in an atmosphere of CO_2 at 1 atm. pressure there is at equilibrium at 900,° 0.33 mol. CO_2 present as carbonate, while at 960° and 1000° the corresponding amounts are 0.28 and 0.24 mol.[1]

In the magma, therefore, the proportion of gas and liquid is a function of chemical composition, of temperature, and especially (because of its relation to concentration) of pressure. In the process of crystallization the concentration of that portion of the volatile components which does not crystallize out as compound or as solid solution will increase relatively in the residue. Eventually, therefore, a fluid solution under high pressure will remain, which will escape whenever an opportunity presents itself, as for instance along tectonic lines. When the volatile components can escape slowly but continuously they will obviously not be under very high pressure, and the amount of material carried by them will be small. Consequently in such cases the main effects are due to the change of temperature and the production of a more or less homogeneous medium by impregnation with the volatile components (especially when water is a factor), which results finally in a fairly uniform recrystallization of the original rock.

The extent of metamorphism is governed in large degree by the nature of the original rock; for instance, by its permeability, which is doubtless one of the chief reasons why limestones in contact with eruptive rocks are much more extensively metamorphosed, and contain a greater percentage of pneumatolytic minerals, than the shales. Moreover, its chemical composition may be a factor, if it is such that reaction may take place between any of its com-

[1] P. Niggli, *Z. anorg. Chemie* (in course of publication).

ponents and the penetrating gases (fluorides, sulphides, etc.). Furthermore, the conditions of formation of the original rock are of importance, as indeed they are with any metamorphic process; for if these conditions were not very different from those which obtained at the period of metamorphic action, the amount of this action would be slight, because there would be either no tendency toward another equilibrium or only an instability of single phases.

Usually in cases of contact metamorphism there is a small pneumatolytic addition of material, which may be temporary or permanent. If it consists essentially in a saturation with water vapor it will materially favor recrystallization. In the rock close to an eruptive contact there is often observed an increased concentration of alkalies, especially of soda. In sediments—clays and shales—there is usually more potash than soda, a predominance which is correlated with the relative solubility or stability of potash- and soda-minerals, since clastic sediments are in large measure merely residues, the least soluble portions of the original material under the particular conditions to which it has been subject. Contact-metamorphosed shales and schists, on the other hand, often have a much larger soda-content than the unaltered material of the same horizon, as is illustrated by the following analyses of rocks in the Christiania region, as given by V. M. Goldschmidt.

	Contact Metamorphic	Unchanged Schists from the Same Locality	
		1	2
SiO_2	54.95	54.43	49.46
TiO_2	1.15	.....	0.89
Al_2O_3	16.32	15.93	19.44
Fe_2O_3	2.95	8.42	1.37
FeO	5.66		6.03
MnO	0.16	.....	0.11
MgO	4.89	3.50	4.68
CaO	3.88	3.56	3.16
Na_2O	*5.56*	*0.74*	*1.55*
K_2O	3.56	3.44	4.12
C	.....	0.66	.....
Loss on ignition	0.71	7.19	6.37
FeS_2	.....	.....	0.29
CO_2	.....	.....	3.70
	99.79	97.87	101.17

The same observation has also been made by others, among them L. Hezner[1] in schists of the Gotthard region. In this case the additions did not take place at the period of intrusion, but during the tectonic disturbances, a fact which shows that the phenomenon is not due to a difference of volatility of soda and potash compounds at high temperatures, but to differences of solubility. Corresponding to this, the solutions emanating from eruptive rocks usually contain more soda than potash, a fact which is correlated with the high soda content of sea-water.

The occurrence of relatively small amounts of such substances as hydrofluoric acid, boric acid, hydrofluosilicic acid, which often are present in magmatic solutions and emanations, can be noted in the mineral content, though the general characteristics of the rock are otherwise altered but little. Such additions produce certain minerals characteristic of contact-metamorphic rocks: such as fluorite (F), scapolites (chlorides), axinite, tourmaline (B), ores (S, As, Sb), lime silicates or quartz in metamorphosed carbonates (Si).

If intrusion proceeds relatively rapidly, or if solutions (fluid or liquid) at high pressure remain over from the process of solidification, there will be an intensive penetration of the surrounding rock with magmatic material. The escape of the magmatic solution follows along the lines of least resistance, producing numerous veins and dykes; in originally sedimentary rocks the direction of these is that of the stratification, or in case the rock has been (or is simultaneously) subject to tectonic disturbance, they lie in the direction of the cleavage planes produced thereby. An interfoliation of the rock may therefore be produced in this way.

A further consequence of intense penetration with hot magmatic material is a considerable rise of temperature in the surrounding rock, which produces the characteristic phenomena of thermometamorphism and *Sammelkristallisation* (increase in size of the crystals). In the neighborhood of injected veins the crystals of a mineral are commonly larger than they are at some distance from it. The tendency to growth of crystals exists because small crystals of any substance are unstable with respect to larger crystals.

[1] *Neues Jahrbuch f. Min.*, Beilage Band XXVIII (1908).

Growth actually takes place only when the temperature is high enough for the rate of growth to be appreciable.

The occurrence of this phenomenon in precipitates in contact with water is frequently used to advantage in analytical operations, to coarsen the grain of precipitates and so render them easier to filter. It has also been demonstrated on a system containing no water by Rinne and Boeke,[1] who, by heating up calcite crystals of various sizes in gas-tight bombs to high temperatures (1,000°) for considerable periods, found that the grains had become nearly uniform in size. Of similar import is the well-known fact that a glass may be made to crystallize in a temperature region in which it is by no means fluid, the optimum effect occurring usually at a temperature 20°–50° below its eutectic temperature.

When rock fragments are surrounded by liquid magma, it will act as a solvent and corrode the fragments in a manner depending upon the temperature and chemical composition of both. On the other hand, the solid particles act as crystal nuclei toward the magmatic solution, at least if its temperature is such that crystallization is possible. It is to be noted that rock transformations, due to partial meltings and recrystallizations, may take place at temperatures far below the melting-points of the individual minerals present; for such processes the positions of the various possible eutectic points are the essential criteria. Thus it is well known that mixtures of solid components in eutectic proportions can be liquefied by long-continued heating at the eutectic temperature, which may be very much lower than the melting-point of any one of the components.

The question as to whether solid fragments sink or float in the magma cannot be decided by density measurements made at ordinary temperature, but its answer involves a knowledge of change of volume with temperature, and requires, in addition, that the influence of viscosity and of gas evolution be considered.

R. Brauns has lately directed attention to a new type of metamorphism, the so-called pyrometamorphism, a term which he has used to denote the effects of hot gases in partially melting[2] some

[1] *Tschermak's Petr. Mitt.*, XXVII (1908), 293.

[2] This idea has also been made use of by Daly in his paper on "The Nature of Volcanic Action," *Proc. Am. Acad.*, XLVII (1911), 92–93.

of the ejected blocks found in the Laachersee region. Such corrosion phenomena are also common, for instance, in biotites of injected rocks. This action of hot gases is identical with that of a blast flame, except that some addition of material may at the same time take place.

CONCLUSION

In the foregoing pages we have endeavored to set forth the most important general principles concerned in rock metamorphism—a general term which includes a number of special cases (e.g., contact metamorphism) all of which, however, differ only in the degree of predominance of one (or more) of a definitely limited group of effective factors. These factors are: temperature, uniform pressure, stress (non-uniform pressure), and gross composition of the system at the time of metamorphism; the same, namely, which determine the equilibrium of the relatively simple chemical systems hitherto investigated experimentally. The knowledge gained from a study of these simple systems may be used as a basis for a prediction of the general character and significance of metamorphic processes; though in applying the principles one must always bear in mind those circumstances which oppose the attainment of a state of true equilibrium, such, for example, as slowness of reaction or the formation of metastable intermediate products.

Now, although the general character of the process may be predicted, no particular statement as to the effects produced in a given system by change of any of the above factors can yet be made, owing to lack of the requisite quantitative data. In this connection it is to be noted that the general application of experimental results which obtain for a given system under given external conditions to another system under similar conditions, or even to the same system under widely differing conditions, is subject to considerable limitation. Conclusions drawn from such extrapolation of experimental evidence will commonly be of little value, and may be altogether misleading; moreover, one may as well guess the final result as arbitrarily choose the data required in calculating it. From this we see that the application of the above simple principles, which determine rock metamorphism, to the complicated rock systems will be no simple matter, but will require

extended experimental investigation and a long time. In such investigation the first thing necessary is a definite conception of the general processes of rock metamorphism; this it has been the purpose of the authors to present in the foregoing pages. The choice of particular problems in this large field will doubtless be aided greatly by a study of natural mineral associations from the physical chemical standpoint, a study which at the same time will certainly provide us with information bearing directly on the problems at issue.

WASHINGTON, D.C.
July, 1913

THE PRIMITIVE STRUCTURE OF THE MANDIBLE IN AMPHIBIANS AND REPTILES

S. W. WILLISTON
University of Chicago

There has been much uncertainty and doubt as to the structure of the mandible in the early amphibians and reptiles. The abundant material of paleozoic vertebrates in the University of Chicago museum has enabled me to determine beyond reasonable doubt, not only the intimate structure of the pelycosaurian and cotylosaurian mandibles, but also that of a very typical temnospondylous stegocephalian. A full discussion with figures of the various forms in which I have determined the structure will be published in a more extensive work on Permian vertebrates next June. For the present I give only the more essential, newly discovered characters in the cotylosaurian genus *Labidosaurus* and the stegocephalian *Trimerorhachis*, accompanied by figures of the latter. A brief description of the structure in *Dimetrodon* has already been published by me in *Science*.

The coronoid of *Labidosaurus* extends from about the seventh tooth along the alveolar margin to about one inch back of the teeth, appearing on the inner side of the outer wall of the meckelian orifice as a narrow, thin bone. The bone forms the anterior wall of the orifice, joining the prearticular much as it joins the angular in the alligator. The prearticular covers the inner side of the mandible posteriorly much as in *Trimerorhachis*, though not so broadly, and extends forward below the coronoid to about opposite the anterior end of the inframeckelian foramen, where it joins the splenial. The splenial, as usual, enters into the symphysis anteriorly and extends back to the inframeckelian orifice about opposite the last tooth, and forms also part of the inferior margin of that foramen; it is only narrowly visible on the outer side of the mandible.

The arrangement of the elements in *Trimerorhachis* will be shown in the figures better than I can describe them. The coronoid (*cor*), in its relations and position, is almost precisely like that of *Labidosaurus*, except that it is broader anteriorly, and does not extend quite as far forward. It bears the small teeth opposite the posterior dental series. The prearticular (*pa*) is a very broad bone, rather loosely united with the adjacent elements in most of the specimens. Its lower margin posteriorly forms the upper margin of the foramen for the chorda tympani. It borders, as usual, the upper inner margin of the posterior meckelian foramen

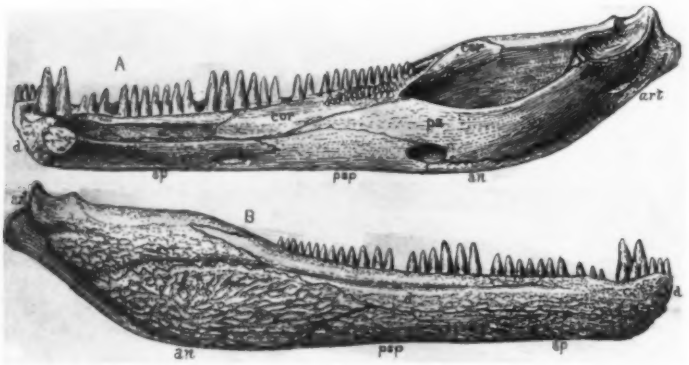


FIG. 1.—Right mandible of *Trimerorhachis alleni* (?) Case, four-ninths natural size: *A*, from within; *B*, from without.

and then continues as a slender projection nearly or quite to the hind end of the splenial. The splenial (*sp*) has precisely the same relations anteriorly as in the cotylosaurs and pelycosaurs, entering more or less into the symphysis and extending back to the anterior margin of the anterior meckelian foramen, and beyond it above to a variable extent. These relations are confirmed in some twenty different mandibles. Lying back of this splenial there is another element corresponding to the posterior part of the splenial in *Labidosaurus*, except that it does not extend beyond the posterior meckelian foramen. It overlaps broadly above the anterior end of the prearticular. I propose to call this bone the

postsplenial, or, if preferred, the *postopercular*. The presence of this element has been definitely confirmed in *Diplocaulus* by Mr. Herman Douthitt, Fellow in Paleontology of the University of Chicago, who will shortly publish figures and descriptions of the cranium and mandible in this genus.

A bone corresponding to that which I call the splenial has been determined in several stegocephalian mandibles; but under a misapprehension of the true relations of the bones posteriorly it has been called the infradentary, after a corresponding element in certain fishes. There can remain no doubt that it is identical with the bone now known to be characteristic of all primitive reptiles, as I have shown, which is certainly the splenial. It is also quite evident that both these bones, the splenial and postsplenial, correspond to the single splenial in the cotylosaurs and the crocodiles. Were we dealing with modern reptiles only, we should be justified in calling the posterior element the true splenial and the anterior one the infradentary. But we cannot conceive of such an anterior development of the posterior bone in *Labidosaurus* and *Dimetrodon* as I have shown to be the case. It is therefore practically certain that it is the posterior bone which has disappeared in the reptiles. Has it fused with the anterior bone? Or has it entirely disappeared? Whatever may be the case, it is quite evident that the bone requires a new name, which I have given it.

I may add that the sutures shown in the figures of *Trimerorhachis* are based upon a prolonged study of more than forty different mandibles of this genus. The sutures separating the articular from the surangular cannot be distinguished in any one of the forty specimens; that between the prearticular and the coronoid is less certain than the others, in its full extent.

FOSSIL FEATHERS AND SOME HERETOFORE UNDESCRIBED FOSSIL BIRDS

R. W. SHUFELDT, M.D.
Washington, D.C.

In addition to the photographs of the slabs of *Archaeopteryx* from the British Museum (*A. lithographica*) and from the Berlin Museum (*A. siemensii*), the material described in the present paper is based upon specimens sent me for the purpose by Mr. Theo. D. A. Cockerell, of the University of Colorado, Boulder, Colo.; by Professor Charles Schuchert, and Mr. C. W. Gilmore. The valuable lot from Professor Schuchert belongs to the Geological Collections of the Peabody Museum of Natural History of Yale University, and those loaned me by Mr. Gilmore belong to the Division of Paleontology of the United States National Museum, in which institution he has charge of the fossil birds and reptiles.

The most important part of this material was photographed by me, and the reproductions of those photographs appear throughout this article. All the figures in the illustrations are reproduced from photographs made by the author direct from the specimens figured.

With respect to the photographs of the two species of *Archaeopteryx*, the one of the British Museum slab was made for me, many years ago, for an illustration to a magazine article I was preparing at the time, and which has long since been published;[1] the other I obtained by copying it from the plate in Vogt's article by means of the camera, it being here reproduced as Fig. 2.[2]

[1] R. W. Shufeldt, "Feathered Forms of Other Days," *Century Magazine* (New York and London, January, 1886), XXXI, No. 3, pp. 352–65. It is Fig. 1 of this article on p. 353 (Fig. 1, below).

[2] Carl Vogt (professor in the University of Geneva), "*Archaeopteryx macrura*, an Intermediate Form between Birds and Reptiles," *The Ibis* (a quarterly journal of ornithology) (London, 1880), IV, 434–56. This is Plate XIII of the article, and is a reproduction of the photograph made direct from the original slab. Professor Vogt's article contains a great mass of valuable information in regard to *Archaeopteryx*, and is, indeed, a veritable classic on the subject, although his views are disputed by some paleontologists, the writer among the number.

FIG. 1.—*Archaeopteryx lithographica*. Considerably reduced. Reproduction of a photograph made for the author from the original slab in the British Museum.

In this article, and referring to the slab of *Archaeopteryx siemensii* (Berlin slab), Professor Vogt says:

There remain the feathers. Here, no doubt, these are birds' feathers, with a median shaft having barbs perfectly formed. The horny substance of

FIG. 2.—*Archaeopteryx siemensii*. By the author after Carl Vogt. Known as the "Berlin specimen." Considerably reduced.

the feathers has vanished, but the model in the fine paste of the lithographic stone is so perfect that the smallest details may be studied with the lens. The new slab shows all the feathers in their place.

The remiges of the wings are fixed to the ulnar edge of the arm and to the manus; they are covered for nearly half their length with a filiform down. None of them project beyond the others; the wing is rounded in its outline like that of a Fowl [p. 445].

What else Professor Vogt says in this article about the feathers of this famous fossil *bird* from the Upper Jurassic of Solenhofen, Bavaria, is not applicable here, where I desire to discuss only the character of fossil *contour* feathers, as well as "downy" ones.

FIG. 3.—Fossil bird (?) from Florissant, Colo. (1908). Loaned by Theo. D. A. Cockerell, of the University of Colorado. Natural size. Reproduction of a photograph by the author.

Fossil feathers have puzzled paleontologists more than once; and not long ago, Dr. Knowlton, of the National Museum, showed me there, in the collections, some specimens that were originally described as "fossil feathers," but were subsequently pronounced, and proven to be, examples of fossil *ferns* of species since described.

Here in the United States nearly all the specimens we have in museums of the fossil feathers of birds—and they are, comparatively,

of great rarity—have been found in the Florissant formation at Florissant, Colo. Fossil bird feathers, however, have been found in various parts of Europe and elsewhere in the world.

After I had the conversation with Professor Frank H. Knowlton in regard to the mistaking of fossil ferns for birds' feathers, Mr.

FIG. 4.—Specimen shown in Fig. 3, enlarged three and one-half diameters (linear)

Gilmore kindly turned over to me the specimens shown in Figs. 5 and 6 of this article, they being the best of several others the National Museum had like them, and practically all they had. This is a single slab, fortunately cleft, that shows the impress (*V*) and fossil remains (*A*) of four primary feathers of a bird's

FIG. 5.—Bird feathers. Tertiary: (Oligocene), Florissant Beds, Florissant, Colo. Lacoe Coll. U.S. Nat. Mus. Reproduction of the photograph of the specimen made by the author. Natural size.

wing. They are long and rather narrow, but quite as well preserved, and in precisely the same way as those described for *Archaeopteryx* by Professor Vogt in a previous paragraph. In this specimen, too, there is evidence of some smaller feathers collected about a point from which the primaries diverge. It would appear that maceration had far progressed before these four feathers settled down at the place where they eventually fossilized, and that they had been held together by a single piece of integument at a point common to their attachment to the four apices of the calami. This might likewise have happened had some animal, in devouring this bird, torn off the four feathers, all clinging to a single piece of skin, and that have become separated from the rest of the bird. These feathers belonged to a bird about the same size as, or one perhaps somewhat smaller than, the *Palaeospiza bella* of Allen, and it is quite possible that they may have come from the wing of an individual of that species (cf. Figs. 5 and 6). Both are from the Florissant formation of Colorado.

As it appeared to be eminently desirable that I compare these feathers with those beautifully preserved ones of *Palaeospiza bella*, I made the attempt to borrow the original specimen of that bird, which I was given to understand was the property of the Boston Society of Natural History. In this I was disappointed; and it now appears that that famous slab and invaluable specimen has been *lost* for a number of years. Only recently, both Dr. J. A. Allen—its original describer—and Dr. Glover M. Allen, secretary of the aforesaid society, have written me that, after several most exhaustive searches, not a trace of the specimen can be found, and no clue has been discovered leading to its place of concealment, or in whose possession it was last.

Through the kindness of the librarian of the United States Geological Survey, I was enabled to borrow there a copy of Dr. Allen's description of his *Palaeospiza bella*, and this is now before me.[1] As but few ornithologists in this country and abroad know

[1] J. A. Allen, "Description of a Fossil Passerine Bird from the Insect-bearing Shales of Colorado," *Bull. U.S. Geol. and Geog. Surv.* (F. V. Hayden, U.S. Geol.-in-Charge), IV, No. 2, Washington, May 3, 1878, pp. 443–45; Plate I; Figs. 1 and 2. A most interesting brochure.

FIG. 6.—Bird feathers. Tertiary: (Oligocene), Florissant Beds, Florissant, Colo. Lacoe Coll. (V), 2 slabs. No. 4225, Coll. U.S. Nat. Mus. Reproduction of the photograph made by the author. Natural size.

of the appearance of this, "the first fossil passerine bird discovered in North America," although, as Dr. Allen remarks, "birds of this group have been known for many years from the Tertiary deposits

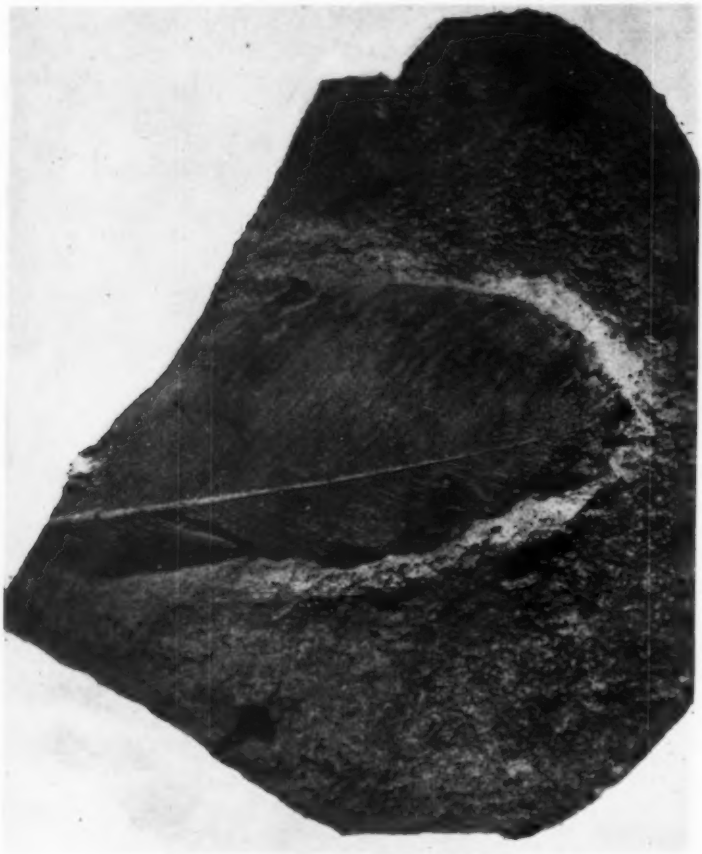


FIG. 7.—Bird's feather. Fresh-water chalk deposits. Gánócz. (Vogelfederabdruck in diluvialem Süsswasser-Kalkstein, Gánócz [Kom. Szepes].) Natural size. By the author after Koloman Lambrecht.

of Europe," I must believe that his figures of it, herewith reproduced, will be found to be useful.

Unfortunately, in this specimen everything anterior to the posterior margin of either orbit was not obtained by the collector; so it is quite impossible to state positively that this bird was a "Fringilline" bird. Indeed, Dr. Allen himself states in his paper that "the absence of the bill renders it impossible to assign the species to any particular family" (p. 443). By the aid of my camera I made a somewhat reduced copy of the plate illustrating this contribution, and it is here reproduced as Fig. 8, with the additional figure beside it as in the original.

With respect to the fossil feathers here shown, Dr. Allen further states:

> The specimen bears also remarkably distinct impressions of the wings and tail, indicating not only the general form of these parts, but even the shafts and barbs of the feathers. . . . . The most remarkable feature of the specimen is the definiteness of the feather impressions. Both the shafts and barbs are shown with great distinctness in the rectrices, and the tips of the primaries of one wing are also sharply defined, overlying the edge of the partly expanded tail. The tip of the opposite wing can also be seen beneath the tail.
>
> Another specimen from the same locality, and probably representing the same species, consists of the tip of the tail and about the apical third of a half-expanded wing [here shown in the smaller slab in Fig. 8]. In this example the tail is also pointed and graduated. About seven of the outer primaries of the wing are shown with great distinctness, and two others can be easily made out. The third primary is the longest; the second is slightly shorter; the first and fourth are about equal. There are also in the collection three detached contour feathers of small size, but whether pertaining to the same species as the other specimens cannot, of course, be determined.

From near the same locality, Dr. Allen, in 1871, obtained a few distinct impressions of feathers from the same Florissant shales; but he, in so far as I am aware, never published a specific description of them.

When visiting at my home in the spring of 1913, Mr. Cockerell informed me that it was not a rare event to meet with fossil feathers in those beds similar to the ones here shown in Figs. 5 and 6.

It was Dr. F. V. Hayden, in 1869 I believe, who discovered the first fossil feather of a bird in North America, it having been obtained in the fresh-water Tertiary deposits of Green River, Wyo.—a locality where so many fossils have been collected. Marsh described this specimen as "the distal portion of a large

FIG. 8.—*Palaeospiza bella* Allen. By the author after Dr. J. A. Allen's figure. Somewhat reduced. The additional slab to one side is of Fig. 2 from Allen's paper, which he suspected belonged to another specimen. (Fully referred to in the text of the present paper.)

feather, with the shaft and vane in excellent preservation."[1] This specimen I have never seen, and I am unable, at the present writing, to say where it is deposited.

Very fine, as well as large, fossil feathers of birds—and most perfectly preserved—are also found in various parts of Europe; one of these is here shown in Fig. 7, it having been photographically copied by me from Tab. I to a most valuable article on fossil birds, which appeared a year ago in the official publication of the Königlich Ungarische Ornith. Centrale, a copy of which was kindly sent me by its author.[2]

On the fourteenth of June, 1913, Dr. Charles Schuchert, curator of the Geological Department of the Peabody Museum of Natural History of Yale University, sent me for description a number of fossils, most of which were of birds and birds' feathers, and all of the last two are utilized in the present article.[3]

Fig. 9 shows a large fossil feather that evidently belonged to a bird of considerable size. It is one of those sent by Dr. Schuchert, and was probably found at Green River, Wyo. (Cat. No. 1227). It is the distal extremity of the feather—about 65 mm. of it—showing the shaft and the soft vanes on either side, the latter being somewhat disturbed proximally. This structure is of an extremely delicate character, and, if really a bird's feather, it was of the

[1] O. C. Marsh, *Amer. Jour. Sci. and Arts*, 2d ser., Vol. XLIV (1870), 272.

[2] Koloman Lambrecht, "Fossil Vögel des Borsoder Bükk-Gebirges und die Fossilen Vögel Ungarns," mit 4 Abbildungen und 4 Tafel-Beilagen. Separat abdruck aus dem XIX Bande der *Aquila*, 1912, pp. 270–320. This paper contains descriptions of a large number of fossil birds from the region in question, most of them, if not all, being species still to be found in the avifauna of the Continent.

[3] Dr. Schuchert remarked in his letter of transmittal:

We are sending you today by express, prepaid, a small box containing all of the fossil feathers that we have. On one of the slabs you will also notice two feet of a bird, and in another box there are quite a number of bird bones that were sent Professor Marsh many years ago by Professor Condon. You are at liberty to make use of these feathers in any way you see fit. Should you illustrate them or apply names to them, please place such information with the specimens, so that we may make the proper entries upon our records.

The two fine specimens of *Archaeopteryx* I saw some years ago in Europe, and of course these are by all means the finest cases of preservation of bird feathers. There is at least one other occurrence of a bird feather from the Solenhofen Upper Jurassic, and I rather anticipate there might be more if you would make extensive inquiries in Europe, particularly in Munich. I have looked through Professor Marsh's correspondence and find nothing there in the way of information concerning our specimens other than that given on the labels.

Hoping you are well, I am,

Yours truly,

[*Signed*] CHARLES SCHUCHERT

FIG. 9.—Large fossil bird feather. "Probably from Green River, Wyoming." No. 1227, Peabody Museum of Natural History, Yale University. Photograph of specimen by the author.

semi-plumulaceous kind. This specimen is upon a very thin slab, as may be observed in the figure. There is another faint indication of a small feather upon it, and a nondescript little fossil near the opposite border. It would be impossible to make a correct reference for this specimen or even to predict to what family the bird belonged that possessed it.

Many large birds, belonging to very diverse groups, probably flourished at the time, and it may have belonged to almost any one of them, as those I have in mind would all have feathers, in certain parts of their plumage, something after this order.

Among the material sent there is still another bird's feather of this character from the same locality (No. 1226, Peabody Mus. Nat. Hist.) that I have not figured in this article. No doubt can exist with respect to this being a fossil bird's feather, and one from a rather large bird of some species I am quite unable to determine—evidently one of the large wing-feathers; it shows the distal 70 mm. of it—the vane being, on an average, some 30 mm. transversely. This fossil, or perhaps its impression, is very faint and delicate, the surface of the matrix being almost smooth and flat. It will not be possible to state correctly to what kind of bird this feather belonged; but it may be said in passing that it resembles very closely the feather shown in Fig. 9.

Another slab (No. 1230) has a somewhat faint and feathery fossil upon it that may represent rather large plumulaceous feathers; but they may not be, and I would not care to undertake to decide the point. On the other side of this slab there is a partially broken-off skeleton of a medium-sized fossil fish (No. 861)—a fact mentioned merely to assist in the identification of the slab in the collection hereafter; it is from the same Green River beds of Wyoming, and the character of the thin slab is the same.

Other undeterminable feathers are shown in Figs. 11 and 12 of the present paper (*d*, *e*, and *f*, and *d'*, *e'*, and *f'*). Their museum numbers, the collectors, the beds and localities from whence they came, are, with other data, fully described in the figures throughout this article. In Fig. 12, I strengthened the fossils by pen and india-ink to give their outlines better. Nothing definite can be given about these as they are altogether too fragmentary and faint.

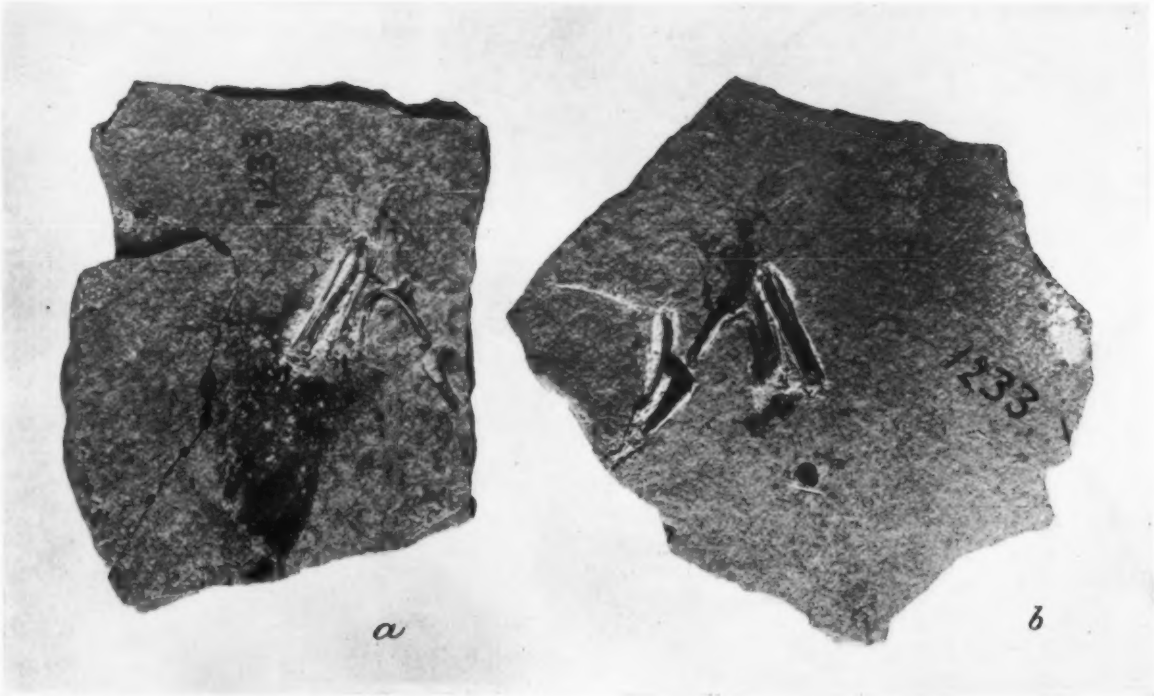


FIG. 10.—*Hebe schucherti*. Natural size. Reproductions of photographs direct from the specimens by the author. No. 1233, Peabody Museum of Natural History, Yale University. Found five miles west of Green River City, Wyo., in the fish cut of the railroad. Found by F. C. A. Richardson of Chicago (1874), with Powell Expedition. It was associated with insects described by Professor Scudder. *a*, slab showing the feathers and impressions of bones. *b*, slab containing fossil bones.

FIG. 10.—*Hebe schucherti*. Natural size. Reproductions of photographs direct from the specimens by the author. No. 1233, Peabody Museum of Natural History, Yale University. Found five miles west of Green River City, Wyo., in the fish cut of the railroad. Found by F. C. A. Richardson of Chicago (1874), with Powell Expedition. It was associated with insects described by Professor Scudder. *a*, slab showing the feathers and impressions of bones. *b*, slab containing fossil bones.

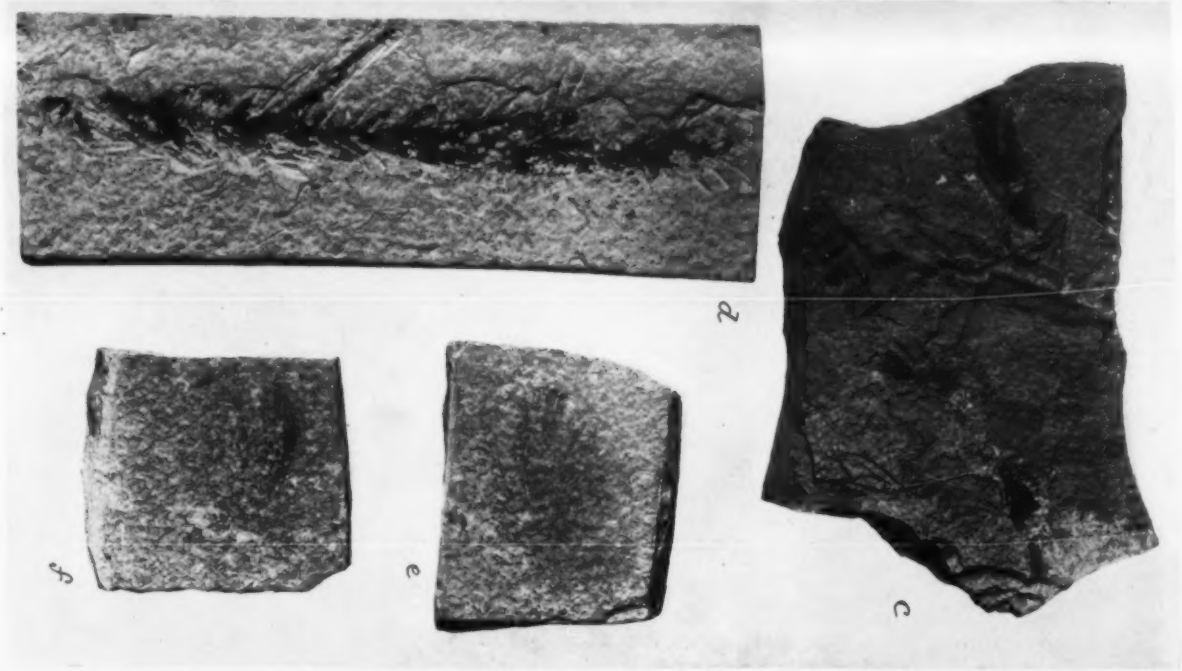


FIG. 11.—*Yalavis tenuipes*. *c*, No. 1231, Coll. Peabody Museum of Natural History, Yale University. (Marked "Bird" January, 1876, by Professor O. C. Marsh.) No further history. Natural size. Photograph by the author. (See Fig. 12, *a*, *b*, *c*, and *d*.) *d*, fossil feather of bird. Orig. No. 988, Cat. No. 1235, Coll. Peabody Museum of Natural History, Yale University. From Green River beds (Eocene). Coll. A. Schoonmaker. Found near Evanston, Wyo. Received July 31, 1877 (see *d'* of Fig. 12). *e* and *f*, two slabs of same specimen. Fossil bird feather, distal portion. Coll. Peabody Museum of Natural History, Yale University. Orig. No. 1013. Cat. No. 1228, Coll. A. Schoonmaker, Bear Lake Valley, Wyo. Came in lot of fishes sent Professor Marsh. Natural size. Photograph by the author. (See Fig. 12.)

The two feathers shown on the slab containing, at least, the pedal remains of the fossil bird described farther on in this paper in all probability belonged to the specimen. One of them is evidently a contour feather (Fig. 12, *c*), and the other from a wing (Fig. 12, *d*).

Similar feathers or feather impressions are also to be seen on other slabs at hand, such as those figured in Fig. 10 (*a*), in Figs. 3 and 4, and an unfigured one (No. 1232, Peabody Mus. Nat. Hist., Green River, Wyo. From F. V. Hayden) which I am very much in doubt about, as it so closely resembles some of the bits of fossil ferns shown me recently by Dr. Knowlton.

I now pass to the descriptions of the slabs belonging to the Peabody Museum, which contain the fossil remains of small birds heretofore undescribed. These are fully recorded in Figs. 10–12, where the required museum data are set forth. Two such birds are at hand, or rather fossil parts of them; these latter both belonged to small passerine species, and are more or less perfect, as far as they go. These parts, however, are not sufficient to admit of referring either of these birds to the genus to which it belonged. This being the case, I have thought it best simply to give them names by which they may hereafter be known, in order that avian paleontologists may be aware of their existence and of the museum to which they belong.

They may or may not have been from specimens representing genera still in existence in our avifauna; if they are, the generic names may be changed when future material is found, to which some paleontologist, in the years to come, can refer them with *absolute certainty*. As to the specific names, which I have given them below, they will stand for all time, as there is not enough of this material ever to decide upon that point with unqualified correctness. With these few words of explanation, I am sure it will be useful to future researchers in this field to have names attached to these specimens, in that they may be used and referred to in making other studies and comparisons.

HEBE SCHUCHERTI, gen. et sp. nov.

(Fig. 10, *a* and *b*)

The specimen is upon two slabs, one giving the actual bones found (*b*), and the other their impressions with some of the feathers of the wing—apparently the *right* wing.

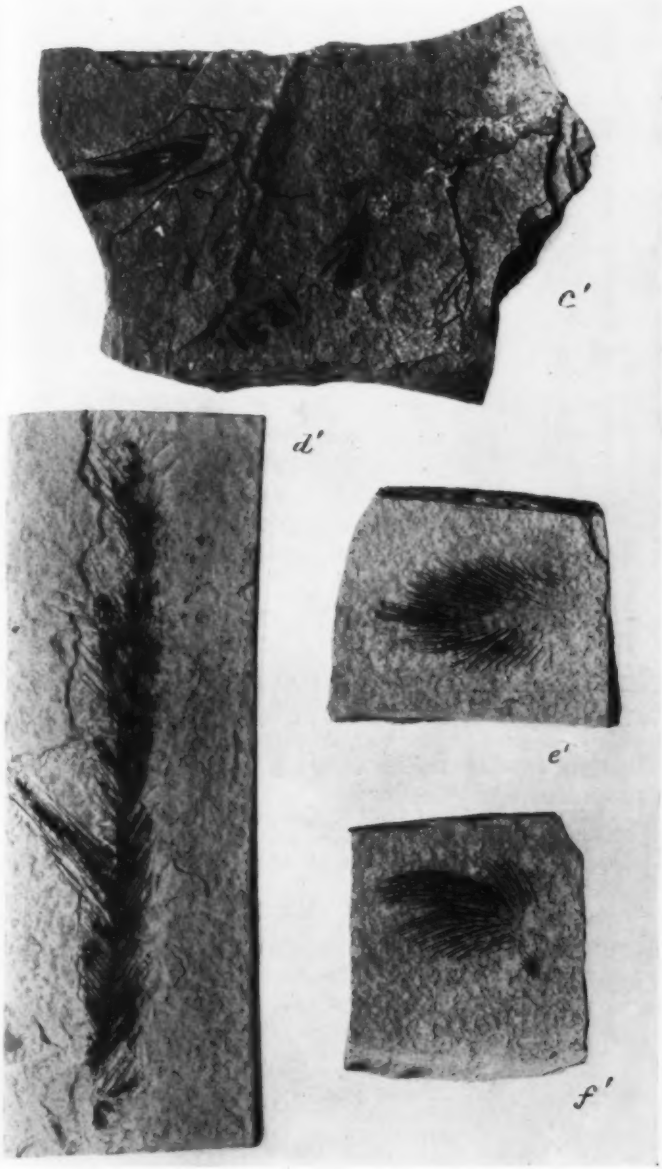


FIG. 12.—*Yalavis tenuipes*. Duplicate of Fig. 11 (see *antea*). Structures to be seen (Fossil) made black by the author, who also made the photographs direct from the specimens. $c' = c$ of Fig. 11, *a* and *b* (on the slab), fossil feet; *c* and *d* (on the slab), fossil feathers. $d' = d$ of Fig. 11; $e' = e$ and $f' = f$ of Fig. 11. Natural size. Same history as given under the previous figure (Fig. 11).

At this writing, the specimens are in the collection of the Geological Department of the Peabody Museum of Natural History, Yale University (Orig. No. 2831, Mus. No. 1233); found five miles west of Green River City, Wyo., in the fish cut of the railroad. Collector, F. A. C. Richardson (1874), Powell Exp. It was associated with insects described by Dr. Samuel H. Scudder.

On the other side of the label accompanying this material, apparently in the same handwriting, I find: "Compare *Pteroptochidae;* see *Ibis*, 1874, p. 19 (July), for sternum with 2 emarginations in *Sternum*." This will be commented upon farther on.

The slabs are light colored and *thin*, and I have so arranged them in Fig. 10 that the fossil bones (*b*) and their impressions (*a*) bear the relation to each other that they would have had they been on the opposite pages of a book, and we had opened it to examine it.[1]

The bones on the slab *b* are as follows (and the *impressions* of all of them are seen on the slab *a*, which, with but one or two exceptions, are brought out with marked distinctness):

1. The *sternum* (in part: ventral aspect).
2. Both *coracoids*.
3. *Os furcula*.
4. A *scapula* (left).
5. *Humerus* (left: proximal moiety).
6. *Ulna* (right: nearly perfect).
7. *Radius* (right: nearly perfect).
8. Bones of *manus* (right: very faintly indicated, and some not exposed).

The feathers have already been referred to in a previous paragraph.

This skeleton belonged to an adult bird about the size of a cactus wren (*Heleodytes*).

The sternum.—Upon very close and careful examination with a high-power lens, we are enabled to observe the fact that the posterior margin of the sternum of this bird possessed two notches upon either side of the keel or carina; there is just enough of the bone

[1] On the opposite side of the slab (*b*) there is a small fossil fish, lacking three-fourths of the fore part of the skull; approximately, it had an extreme length of about 76 mm.

in sight to make certain of this.[1] It is the right side of the body of the bone that is exposed in the specimen; and, as its posterior border had *four* notches—that is, two on either side of the carina—the *sternum* of that bird differed in this particular from all *typical existing* passerines as they now occur in North America, at least north of Costa Rica.[2]

Many years ago, in speaking of the *Pteroptochidae*, Sclater pointed out that this assemblage "must remain, therefore, as an independent family of themselves, to be placed, according to my views, at the end of the Tracheophonine section of the Passeres, and at once distinguishable from all other Passeres by the posterior margin of the sternum being doubly emarginated as in the *Pici* and many *Coccyges*."[3]

That this bird was a passerine species with a four-notched sternum, and not a cuckoo or a woodpecker, is at once evident when we come to examine the remainder of that bone, and find that it possesses a large manubrium which is *bifurcated* anteriorly, thus producing two diverging apophyses, as is the case in the sternum of any true passerine form.[4] This sternum has a mesial length

[1] See note above (on original label) in regard to sternum of the *Pteroptochidae*.

[2] I have not examined the sternum in *Scytalopus argentifrons* of Costa Rica (see Ridgway, *Proc. U.S. Nat. Mus.*, XIV [1891], 475; Sharpe, *Hand-List*, III, No. 13, p. 5). Possibly it may have a four-notched sternum; but there is no material at my hand either to prove or disprove it.

[3] P. H. Sclater, "On the Neotropical Species of the Family *Pteroptochidae*," *The Ibis*, 3d Ser., No. XV, July, 1874, Art. XXIII, p. 191 (Plate VIII), of *Rhinocrypta fusca*. "The only other known Passerine form in which two emarginations are present on each side of the posterior margin of the sternum is the Australian genus *Atrichia*. Whether this form certainly belongs to the *Pteroptochidae* cannot be positively ascertained until the structure of its larynx is known; but I have little doubt that such is the case. There is a sternum of *Atrichia rufescens* in the Cambridge Museum."

To this I may add that on this date (July 1, 1913) there is not an alcoholic specimen, nor a vestige of a skeleton of any of the species of the *Pteroptochidae* in the collections of the U.S. National Museum for anatomical examination.

A. H. Garrod presented a sternum of *Hylactes megapodius* to the Museum of the Royal College of Surgeons of England; but I have never seen the specimen (S.S. 2660) (*Cat. Mus. R. Coll. of Surg. of Eng.*, 1891, p. 123).

[4] R. W. Shufeldt, Fig. 58 in *Key to North American Birds* (Vol. I, E. Coues, 5th ed., p. 151). This figure gives a ventral view of the "typical passerine sternum of the robin (*Planesticus migratorius*)," and in it the bifurcations of the manubrium of the bone are well shown.

of 15 mm., measured from the median anterior point of the posterior one on the carina.

A *coracoid* is 11 mm. long, being considerably expanded below, and developing a small process at its outer sternal angle. The bone is straight, and otherwise presents the usual passerine characters.

The *os furcula* is of uniform caliber with respect to the clavicular limbs, and not especially stout. It is of the broad U-shaped form, with the hypocleidium (if present) not exposed.

A *scapula* appears to be somewhat slender, though rather dilated and curved outward, distally. It has a length of about 11 mm.

Only a part of the left *humerus* is preserved in sight, and this exhibits some of the effects of pressure; it presents nothing worthy of especial note.

Passing to the *radius* and *ulna* of the right arm, we find them in a beautiful state of preservation, and in plain sight. They are quite straight bones, especially the *ulna*, which has a length of about 20 mm.

Bones of *manus* are not sufficiently exposed to admit of examination.

Whether the fossil bones of this bird belonged to a species of a genus in the *Pteroptochidae*, I am not at this time prepared to say; though as far as the evidence goes, there is every indication that it did—that is, barring the present range of those birds which, with one exception, is South American.[1] However, as I found a *flamingo* among Oregon fossil birds, it should not now be a source of surprise were we to meet with the fossil remains of a small South American passerine in the Green River deposits of Wyoming; the climate was entirely different at that age in North America.

It is not likely that this species belonged to any of the existing genera, and I have therefore created a new genus to contain it.

[1] "*Pteroptochidae:* A South American Family of formicarioid passerine birds, typified by the genus *Pteroptochus*, with tracheophonous mesomyodian syrinx, taxaspidean tarsi, operculate nostrils, and ten primaries; the rock wrens. They are small, wren-like birds of skulking habits, especially characteristic of Chile and Patagonia.

"There are about 24 species, leading genera of which, besides the type genus, are *Hylactes*, *Scytalopus*, and *Rhinocrypta*. Some of them are known as 'barking-birds'" (*Cent. Dict.*, p. 4826).

the same being provisional, or until such time when we have more material of both fossil and existing forms wherewith to critically compare it.

Hebe (new genus), the goddess of youth and spring of Greek mythology.

The specific name is in honor of the eminent paleontologist of Yale University, Dr. Charles Schuchert.

YALAVIS TENUIPES, gen. et sp. nov.

(Fig. 11, *c*; Fig. 12, *c'*)

From a study of the figures in the illustrations (fossil bones, etc.) it will be seen that in Fig. 12 (*a*) the specimen consisted of parts of the *left* pelvic limb, being the lower part of the tibio-tarsus; the tarso-metatarsus, and the toes complete. It is of the left limb for the reason that these are the actual bones, and the *inner toe* is to the outer side—that is, the first in order as we examine the foot.

It belonged to a small *passerine bird* of about the size of any one of the North American warblers, such, for example, as the pine warbler (*D. vigorsi*) or a somewhat larger species. The *tarso-metatarsus* has a length of 15 mm., and is, together with the toes, of notably *slender* proportions.

The toe-joints can be easily measured in the figures, as they are exactly of natural size.

The *right* foot of this specimen is doubtlessly to be seen at *b* on the same slab (Figs. 11, 12). Here the phalangeal joints occupy different positions.

These bones belonged to some small passerine bird that cannot as yet be referred to with certainty.

Birds of the same genus and species may or may not be still in existence; the probabilities are that they are not.

This specimen indicates that it belonged to a highly specialized *perching* bird, with very much *curved* claws, and the claw of hallux *not* lengthened as in the larks and their allies.

When we come to consider the vast number of small *passerine* birds that are in existence at the present time; and how many more there may have become extinct, representing such scores of

families, many species of which would possess the skeletal parts of the foot of a size and proportion quite like the one in this fossil, it will be appreciated how useless it would be to express an opinion as to the *family* this bird represented. No such attempt will be made here.

My reasons for creating a new genus for it are set forth on a foregoing page of this article.

Yalavis (Yale and *avis;* the University at New Haven, Conn., U.S.A.; and *avis*, a bird).

The specific name *tenuipes* refers to the slender bones in the foot of the specimen, as seen in its fossil remains.

Early in the summer of 1913, Mr. Theo. D. A. Cockerell, of the University of Colorado (Boulder, Colo.), when on a visit to Washington, handed me the specimen, here reproduced natural size in Fig. 3, for a description and, if possible, a diagnosis.

As the specimen is very small, I had it enlarged, and this latter is reproduced in Fig. 4.

It has no special history beyond having been collected in 1898 at Florissant, Colo.

At first glance, it has the appearance of being the fossil remains of some small bird, or even medium-sized bird, as it is associated with a few feathers. The latter consist of down (?), contour feathers, and one feather from a wing. The bones, whatever they may be, are in *pairs*, and evidently not materially disturbed.

By the aid of a two-inch objective on a powerful microscope, I brought these up to a large size for critical examination. To some extent they appear as though they might be a pair of *coracoids* and some part of the *sternum;* but as here exposed, I find that this suggestion cannot be verified.

It may be some part of a bird's skull; the smaller pair of bones, *pterygoids*, and the larger ones—partly exposed—*palatines;* but I doubt it. And were this so, the feathers would probably have belonged to the *head*—a fact militated against by the presence of what is undoubtedly a *wing-feather*.

These bones may have belonged to some other animal than a bird, or it may even have been some invertebrate form (crustacean), and the association with feathers entirely coincidental, as we would

find the fossil bones of some small mammal mixed up with, or in the same matrix associated with, those of some large raptorial species of bird that had eaten it just prior to its death. Such a case I have recently had good reason to suspect.

Pressure, fracture, and a number of other causes have caused fossil bones of animals of all sizes (vertebrates) to change their form and appearance. This must be borne in mind when making examinations of such material as we have here.

Then, when incased in a matrix and only *partially* exposed, bones have a very different *appearance* from what they have when seen in entirety. Every paleontologist of experience is aware of this fact.

Let us imagine that the fossil base of the superior mandible of a male surf scoter (*Oidemia perspicillata*) was the only part exposed in a dense matrix; would anyone suspect it of being a *duck?* When some bones are but partially exposed in the matrix, they often resemble others of the skeleton when the latter are more fully in view. For example, we may so far immerse the distal end of some avian *humeri* that the part left exposed may, in some instances, very much resemble the coracoid of some other kind of bird; and there can be no end to such instances.

This may easily be the case with the specimen here being discussed. The larger pair of bones seen in the enlargement in Fig. 4 may be the proximal extremities of a pair of humeri, palmar aspects, and only partly exposed, and the small pair (?) below them some part of a dorsal *vertebra*. It is quite possible.

In short, I am of the opinion that a reference—a correct reference—cannot be made for this specimen, beyond its being probably *bird*, and under the circumstances it would be useless to give it a name.

The fossil bird bones from Silver Lake, Ore., mentioned in Dr. Schuchert's letter on a previous page of this article, are, in all particulars, like those belonging in the Cope collection of the American Museum of Natural History of New York City. Very recently I have fully described that entire collection, and this description will appear as a bulletin of that institution with upward of 600 figures on plates.

The specimens now before me can be compared with those figures, thus rendering any description of them here superfluous.

It may be said, however, that in the lot now before me I find two *cervical vertebrae*, probably of an adult female of the western grebe (*A. occidentalis*); a portion of the right ramus of the mandible of some species of duck (?); bits of shafts of long bones (*humeri, ulnae, radii*, etc.), not determinable; a toe-joint, and the distal end of a *tibio-tarsus* (No. 1236), not determinable with certainty; a ray from the pectoral fin of a fish, proximal extremity—a bone also discussed in my forthcoming memoir.

THE VOLCANOES AND ROCKS OF PANTELLERIA

HENRY S. WASHINGTON
Geophysical Laboratory, Carnegie Institution of Washington

PART I

INTRODUCTION

Since the first half of the last century, when Pantelleria[1] figured in the controversy over von Buch's theory of craters of elevation, the geology of the island has been described only by H. Foerstner and A. Bergeat. Through Foerstner's researches the island has become classic in the annals of petrography, because of his discovery there of soda-microcline and the peculiar hornblende, cossyrite, as well as of the occurrence of the remarkable group of pantellerites.

In view of the interesting character of its rocks and the rather early date of Foerstner's descriptions and analyses, a re-examination of the island was considered to be desirable. Pantelleria was, therefore, visited in September, 1905, in the course of a trip to the western Mediterranean, undertaken for the Carnegie Institution of Washington.

During my stay I met with the utmost courtesy and hospitality, and it is a pleasure to record my thanks to friends on the island, among whom may be specially mentioned Captain G. Herrera, Captain A. Pocobelli, Lieutenant A. Innorta, and Doctor S. Granone. To Professor J. Volney Lewis I am indebted for making the photographs of the rock sections.

GENERAL DESCRIPTION

The island of Pantelleria lies about midway between Sicily and Tunis, rising steeply from depths of over 400 fathoms in the broad, deep channel which separates Sicily from Tunis, near the edge of the Adventure Bank. It is noteworthy that the volcanic Linosa to

[1] Attention may be called to the fact that this is the proper spelling of the name, being that used on all the official Italian maps. The chief accent is on the *i*, not the second *e*.

the southeast rises out of the same channel and is surrounded similarly by deep waters, while the neighboring limestone islands of Lampedusa and Malta are inside the hundred-fathom line, on the edges of the shallow banks which border, respectively, the east coast of Tunis and the south coast of Sicily.

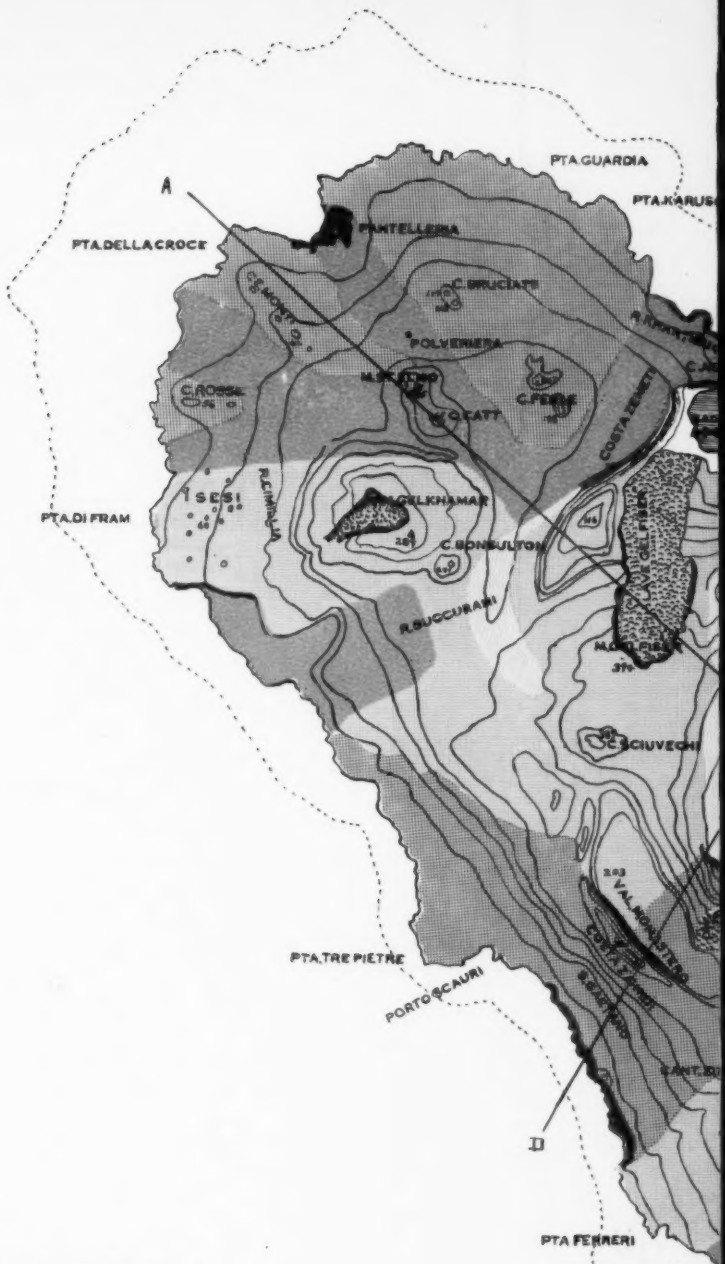
The island is elliptical in shape, with a length of about 13.5 kilometers from northwest to southeast, a breadth of about 8 kilometers from northeast to southwest, and an area of 33.3 square kilometers. Seen from the sea it presents a roughly mountainous and forbidding appearance, which is increased by the prevailing dark color of the rocks, so that it is often spoken of as "L'Isola Nera," the Black Island.

HISTORY

Pantelleria was inhabited in prehistoric times by a people of unknown race, who have left traces of their occupation in the peculiar constructions which are known as *sesi*, found only in the northwestern part of the island (Fig. 1). These are built of rough blocks of lava and are shaped like an elongated dome with a length of 40 to 50 feet, a width of about half this, and a height of from 15 to 25 feet. Each contains several small chambers, separate from each other, and entered by a rather small opening near the ground. In many respects they are almost unique, but they show some analogies with the *talajots* of the Balearic Islands and the *nuraghi* of Sardinia. These latter, however, are better constructed and far more elaborate, and evidently belong to a higher type of civilization than that of Pantelleria.

The island was known to the Greeks, who called it Κοσσοῦρα (Strabo), Κοσσύρα (Ptolemy), and other variants, while the Romans named it Cossyra (Ovid and Pliny), Cossyrus (Silius Italicus), Cosura (Seneca), etc. The origin of its present name, which dates from about the fourteenth century, is unknown, and its etymology uncertain. Its history has been briefly sketched by D'Avezac,[1] who, however, does not mention the *sesi*. According to him it was probably first inhabited by the Phoenicians or Carthaginians. Traces of this remote occupation are still to be found in the dialect

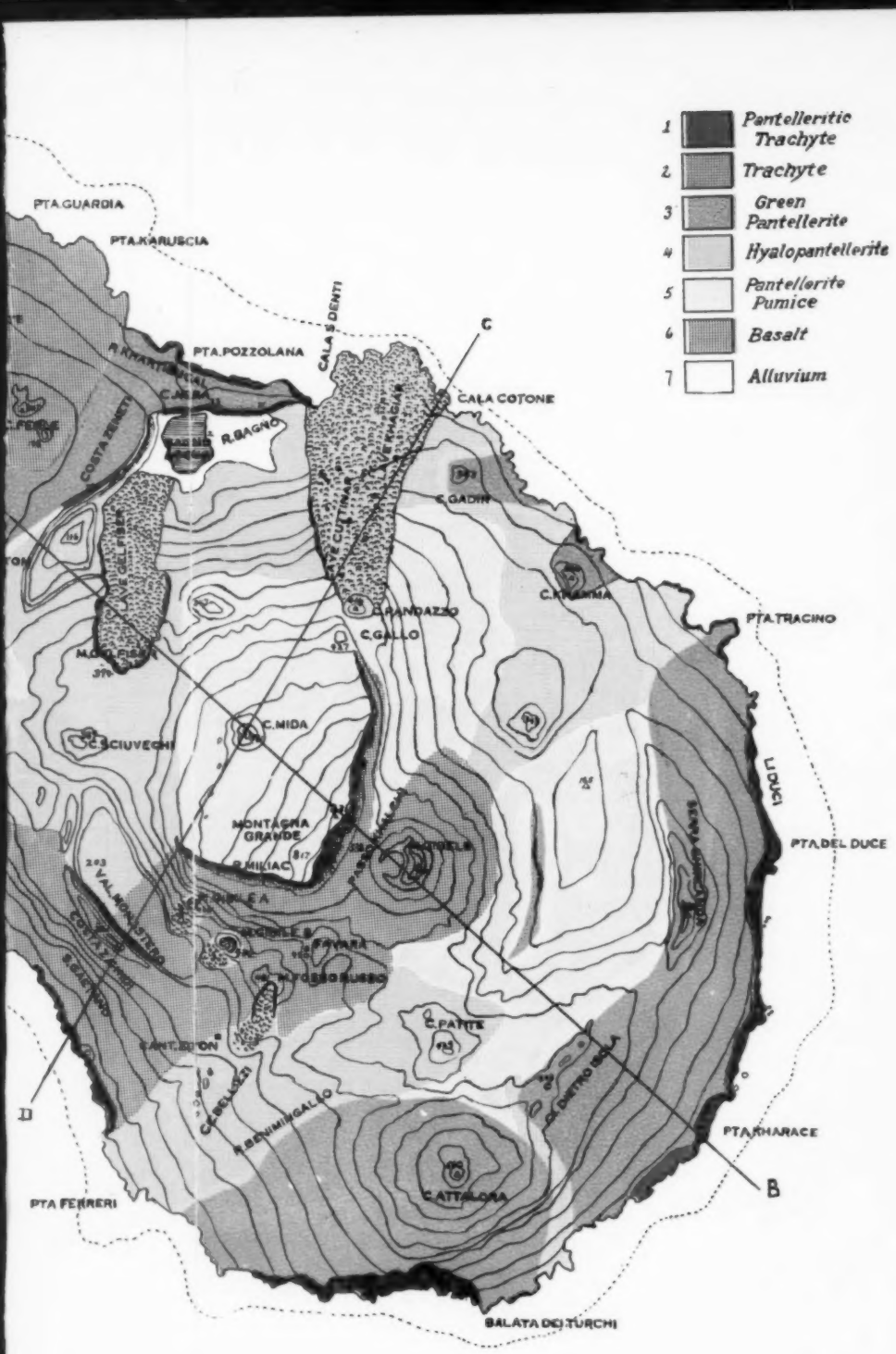
[1] D'Avezac, *Iles de l'Afrique*, Paris, 1885, p. 104.



MAP OF PANTELLERIA

SCALE 1 : 64.000

1 2 3 4 5 Km.


1 Pantelleritic Trachyte
2 Trachyte
3 Green Pantellerite
4 Hyalopantellerite
5 Pantellerite Pumice
6 Basalt
7 Alluvium
PTA.GUARDIA
PTA.KARUSCIA
CALA DEI DENTI
PTA.POZZOLANA
C
CALA COTONE
R.BAGNO
COSTA DEI DENTI
C.GADIR
C.GRANDE
C.PANDAZZO
C.GALLO
PTA.TRACINO
C.NIDA
C.SCIUVECHI
MONTAGNA GRANDE
LUCKI
PTA.DEL DUCE
VAL MONASTERO
C.PANTE
PTA.KHARACE
D
B
C.ATTALORA
PTA FERRERI
BALATA DEI TURCHI

and in many of the topographic names. From this Semitic period dates a coinage which Head[1] refers to the second century B.C. Cossyra figured in several episodes of the Punic wars, but on the fall of Carthage became Roman, and another series of coins dates from this epoch.[1] It seems to have had a reputation for roughness and inhospitality and is mentioned by Seneca as one of the most undesirable places of exile.

FIG. 1.—Sese (prehistoric dwelling)

It was captured by the Moors in 835 A.D., who called it Qussra, a name by which it is still known in Arabic. After a stormy period, during which the island was the object of contention between the Moors and the Norman kings of Sicily, it became part of the kingdom of Sicily, and thence passed under the dominion of the present kingdom of Italy.

PRODUCTS AND POPULATION

The cultivable parts are mostly given over to vineyards, which produce large, white, and very sweet grapes, which are dried to

[1] Barclay V. Head, *Historia Numorum*, London, 1887, p. 743.

form raisins of a most excellent quality. These vineyards are terraced and surrounded by high stone walls, thus concealing the geology of the areas covered by them. Capers are also cultivated, growing abundantly over the stone walls, while excellent donkeys, noted for their strength and endurance, form the third principal object of export. Olives and figs are also raised.

The island is subject to violent winds, so that fig trees often grow with their trunks horizontal and close to the ground. Vegetable gardens and the small groups of fruit trees are usually protected by high, circular, surrounding walls, such inclosures forming a characteristic feature of the landscape in parts of the island.

Potable water is very scarce, though it is furnished by some of the volcanic springs, one of which forms a public fountain in the town. This is closed except for an hour every morning, when each household is allowed to draw its allotted supply. Some of the steam fumaroles are utilized by herdsmen by covering them with brushwood, which condenses the water and gives rise to small rivulets. The rains are the main source of supply, the water being gathered on the flat, cemented roofs and preserved in cisterns beneath the houses. But after a long dry spell, as at the time of my visit, this supply is likely to fail and the whole population goes on short water rations. Indeed, at times, water has to be imported from Sicily, and an earthquake is likely to cause great distress by cracking the cisterns, as happened prior to the submarine eruption of 1891.

The population numbered 8,619 in 1901, of which about 2,500 inhabit the sole town, also called Pantelleria, on the northwest coast. There is an evident infusion of Moorish blood, dating back to the Saracenic occupation, or even possibly to the original Phoenician settlement. This is specially manifest in the island dialect and in the place-names, many of which show distinctly non-Italian forms, and some of which can be positively identified with Semitic roots. Thus Gibelé is clearly the Arabic جبل (*gebel*) = "mountain,"[1] and Rione Ziton is from زيتون (*zitun*) = "olive," Khagiar is derived from the Arabic حجر (*hajar*) = "stone," Gelfiser probably from جبل فزر (*gebel fozir*) = "burst mountain," Gadir

[1] The same is seen in the name Mongibello for the peak of Etna, and an analogous case is the peak of Ὄρος Βοῦνο (Mountain Mountain) on Aegina, Greece.

possibly from غدير (*ghadir*)="a pond," and Gelkhamar from جبل قمر (*gebel kamar*)="moon mountain." The local term *cuddia*, applied to the small volcanoes and hills, may be derived from حاد (*hadd*)="pointed," and if so, its etymology would be analogous to that of the French *puy* and the Catalan *puig*.

Pantelleria is now used by the Italian government as a penal station (as is Lampedusa), several hundred convicts being at liberty on the island, returning to their quarters at night, and being guarded by two companies of soldiers.

TOPOGRAPHY[1]

Montagna Grande.—The most prominent topographic feature of Pantelleria is the volcanic mass of Montagna Grande, which occupies the center of the island, its summit forming the culminating point with an elevation of 836 meters above sea-level. The mass has suffered extensively from erosion and shows few traces of the original crater. The top consists of a ridge on the east and south, from which the surface slopes rather gently downward toward the west and north. On this slope is the cone of Cuddia Mida, with a small summit crater, so called from being near the center of the island. The summit ridge of Montagna Grande is very precipitous outwardly on the east and south, the scarp varying from 50 to 150 meters in height, built up of massive sheets of trachyte, which sometimes show a rough columnar structure. These scarps do not form a continuous curve, but are roughly straight lines, meeting at an angle of about 110° at the southeast corner at Rione Miliac. From their foot the surface slopes sharply downward to the south and east, the general uniformity being interrupted by several small volcanic cones.

Of these Monte Gibelé, immediately east of the highest point of the summit ridge, is the largest and most important. It is fairly well preserved, its highest point being 700 meters above sea-level, and it shows an almost circular crater, about 100 meters deep and

[1] The accompanying map is based on that of the Instituto Geographico Militare (Firenze, 1877, 1:10000), the geology being based on the map of Foerstner (*Bull. Cour. Geol. Ital.*, 1881, Tav. XI.), and my own observations. The contour lines (interval 50 meters) are only roughly given, and the boundaries of the different geologic areas are only approximate.

200 meters across, which is breached on the southwest side. To the east and southeast of Montagna Grande and Monte Gibelé is the long crescentic ridge of Serra di Ghirlanda, which runs parallel to, and about one kilometer from, the coast, and presents toward the Montagna Grande, over much of its length, a very steep face from 50 to 90 meters high. This is continued to the southwest in the curving line of the Cuddioli dietro Isola, a series of low, isolated hills. At the southwest end of this ridge, and occupying the southern end of the island, is the wooded cone of Cuddia Attalora, 560 meters high, a well-formed, very symmetrical cone, with the remains of a breached crater near the summit. The isolated Cuddia Khamma, northeast of Montagna Grande, appears to be a remnant of a continuation of the Serra di Ghirlanda to the north.

On the southwest and western flanks of Montagna Grande are several small, parasitic cones, namely Fosso del Russo, and two which are both called Monte Gibilé, and which may be designated as Gibilé *a* (north) and *b* (south), to distinguish them from the large cone of a similar name on the east flank. The southwest slopes of Montagna Grande run into the narrow, crescentic Valle del Monastero, which is about 2 kilometers long by half a kilometer wide. This is bounded on the west by the ridge of Costa Zichidi, which shuts in the valley with a precipitous scarp rising 30 to 75 meters above the valley floor. This ridge outwardly slopes rather gently down to the sea, the small harbor of Porto Scauri lying to the west of it and being used instead of the principal harbor when the wind is from the north.

The northwestern and northern slopes of Montagna Grande present a decidedly irregular topography, the original surface having been buried beneath the accumulations from several parasitic cones. Of these the most important are: Monte Gelfiser on the northwest, from which issued the flow called Lava Gelfiser, about 500 meters wide and 2,200 long, extending northwardly to near the Bagno dell' Acqua; and Cuddia Randazzo, on the north, with the large flow known as Lave Cuttinar in its upper portion and Lave Khagiar below. The total length of these is about 3 kilometers and they form a fan whose widest part stretches from Bagno dell' Acqua

on the west to Cala del Cotone on the east, a distance of 2 kilometers along the coast.

Rione di Bagno.—Close to the north coast is a small, irregularly elliptical plain, the Rione di Bagno (Fig. 2). The western part of this is occupied by an oval lake, the Bagno dell' Acqua, with dimensions of about 600 by 500 meters, the surface being only 2 meters above sea-level. The lake is shallow and is evidently the remnant of one which formerly covered the whole of the inclosed

FIG. 2.—Bagno dell' Acqua, from west

area. The Rione di Bagno (including the lake) is bounded on the west by the precipitous east face of a scarp, the Costa Zeneti, which rises to about 200 meters above the lake surface. This ridge is continued to the south and southwest, parallel to the course of the Lava Gelfiser, inclosing the narrow Valle Silhoumen, which is flanked on the east by the towering mass of tumbled lava blocks which constitutes the flow (Fig. 3). To the north the Rione is bounded by a similar though lower (38 m.) precipice, known as Cuddia Nera, which is indubitably a continuation of the Costa

Zeneti, the direction of the scarp face changing from north to east at the northwest angle of the lake. On the east are the rough masses of the Khagiar flow, and on the southeast and south the steep slopes of Costa del Bagno, evidently part of the original north flank of Montagna Grande, while at the southwest corner is the extremity of the Gelfiser flow.

Basaltic area.—The northwestern end of the island offers peculiar features of its own. In general the surface shows a fairly

FIG. 3.—Lava Gelfiser, from Costa Zeneti

uniform, gentle slope away from the central mass of Montagna Grande, the contour lines being roughly concentric about this. On this broad, low, conical base, which has a radial extent of about 4 kilometers and a maximum altitude in the interior of about 200 meters, there are several volcanic cones. These are of two distinct types—a pantelleritic and a basaltic.

Of the former type is Monte Gelkhamar, whose summit, 289 meters above sea-level, rises not more than 100 meters above the general slope on the east, but about 200 meters on the west. In form it is roughly circular, though somewhat irregular, and is

notable for the large barranco which has breached the southwestern side, forming an impressive gulf 600 meters long and 300 wide, with precipitous sides. From this issued the lava flow of Rione Cimillia, on which are to be found the prehistoric buildings mentioned above. The second pantelleritic cone lies about one kilometer north-northeast of Gelkhamar and one and a half south-southeast of the town of Pantelleria. It is crescent-shaped, widely breached on the east, the ridge culminating in the northerly Monte Sant' Elmo (245 m.), on which is a semaphore, and the southerly Cuddia Catt (265 m.). The main mass of this is composed of pantellerite, but on the north flank of Sant' Elmo there has taken place a small, later eruption of basalt, the scorias and lavas of which cover the northern and western slopes, while a flow extends to the north.

The basaltic cones, which are entirely confined to this part of the island, are all small and are less important topographically than they are petrographically. The best preserved are the Cuddie Brucciate and the Cuddia delle Ferle, respectively one and two kilometers southeast of Pantelleria. The former consists of a twin pair of cinder cones, with summits 118 and 114 meters above sea-level, but only about 30 above the base, each with a deep, circular, well-preserved crater. Cuddia Ferle is somewhat higher (207 m.), but with a less well-marked summit crater and with a small subsidiary conelet with breached crater on the north. On the northwest coast are the Cuddie Rosse and Cuddie delli (*sic*) Monti, which are 50 to 60 meters high. Flows of basalt and beds of scoria, derived in part from these cones and probably in part from now hidden vents, cover much of the northwestern coastal part of the island.

The coast line of Pantelleria is, in general, irregular with many small indentations. On the east, southeast, south, and southwest it is mostly precipitous, up to heights of 275 and 200 meters, due to wave action; while on the northwest it is low and formed by the tongue-like ends of the basalt flows.

GEOLOGY[1]

The geological structure of Pantelleria is somewhat complex and has given rise to divergent views. With the exception of some

[1] A short account by me of the geology of Pantelleria was published in *Science* (N.S.), XXVIII (1908), 576. It is practically an abstract of this section.

insignificant beds of travertine and the lacustrine deposits of the Rione di Bagno, the rocks are wholly volcanic. Some fragments of granite found by Foerstner[1] and Soellner[2] in several places on the island indicate that the foundation is of this material. I was not fortunate enough to meet with any of these, but observed fragments of diorite in the lava of the island of Linosa,[3] so that a basement of plutonic rocks may be inferred for the bed of this part of the Mediterranean.

Of the earlier view as to the structure, only mention may be made that Pantelleria was cited as an illustration of von Buch's theory of craters of elevation, the circle of scarps surrounding Montagna Grande being supposed to be due to elevation incident to the formation of this volcano.

Foerstner's views.—Foerstner has discussed the geological structure at some length.[4] In the following summary his rock-names will be retained. According to Foerstner the first eruptions on the granite base were of "phonolite" and "liparite," which uniformly underlie the other lavas, and which issued from a now vanished vent. These were covered by the "andesites" of Monte Gibelé, which was also probably the volcanic center of the lavas of Montagna Grande, then not raised to its present height. From an unknown center of the same epoch are supposed to have issued the "andesites" which form the surface of Costa Zichidi, and which are probably the latest flows of this stage. The next period was that of the eruption of the first pantellerites, especially of the crystalline variety, which poured out of numerous vents all around the large andesitic volcano. The Bagno dell' Acqua is supposed to belong to this period and to have been an explosion crater, while the Cuddia Attalora is a well-preserved parasitic cone of the same period.

The ejection of this mass of lava caused profound dislocations and resulted in the upthrust of the mass of Montagna Grande, which was accompanied by the formation of many subsidiary cones on its flanks and the pouring-out of flows of vitreous pantellerite, as

[1] H. Foerstner, *Boll. Com. Geol. Ital.*, 1881, p. 550.

[2] J. Soellner, *Zeits. Kryst.*, XLVI (1909), 522.

[3] H. S. Washington, *Jour. Geol.*, XVI (1908), 6.

[4] H. Foerstner, *Boll. Com. Geol. Ital.*, 1881, pp. 550–53.

represented by Monte Fosso del Russo, Monti Gibilé *a* and *b*, Monte Gelfiser, Cuddia Randazzo, and others. The faults according to Foerstner, are the cause of, and are represented by, the various encircling scarps mentioned in describing the topography and certain coastal features.

At the close of this period of dislocation the last of the pantellerite cones was formed, that of Monte Sant' Elmo and Cuddia del Catt, after which the lava underwent a change in composition, "by subtraction of silicic acid." The last phase of basaltic eruptions began with an outburst on the northwest flank of Sant' Elmo, and was continued in the small cones of basaltic scoriae and flows of basalt.

Bergeat's views.—The geological structure has also recently been briefly discussed by Bergeat,[1] who cites the mass of Montagna Grande as an example of *Staukuppen* or plug domes, analogous to the spine of Mont Pelée. He adopts the views of Foerstner that the prominent scarps are due to faulting, and indicates on a map the traces of what he considers to be the chief fault-lines, as shown by volcanic cones, scarps, or other lineaments. He calls attention, however, to the fact that a depression would more naturally be supposed to follow the ejection of lavas on a large scale than the upheaval advocated by Foerstner, and would explain equally well the formation of Montagna Grande and the precipitous scarps. On his view the upthrust of Montagna Grande is supposed to be a differential one, due to subsidence of the encircling portion. Bergeat considers that Monte Gibelé was the volcanic center for the whole mass of Montagna Grande and that the two were separated by a fault which he noted in the Passo Khalchi, northwest of the Gibelé crater. With Foerstner, Bergeat apparently considers the Bagno dell' Acqua as a separate center of eruption, since it is indicated on the course of one of his fault-lines, though he does not mention it directly.

Objections to these views.—I am quite in accord with Foerstner as to the general succession of the lavas, especially the earlier date of his "phonolites," "liparites," and the "andesite" of Zichidi, the subsequent eruption of the pantellerites, and the final appearance of

[1] A. Bergeat, *Neues Jahrbuch*, Festband, 1907, pp. 315–17.

the basalts; as I am with Bergeat's conclusion as to the essential structural unity of Montagna Grande and Monte Gibelé, and his conclusion that the latter was the crater of the "andesite" mass. My observations, however, lead me to different conclusions as to the presence of fault-lines and other lineaments, and the origin of the volcano of Monte Gibelé and Montagna Grande, the ring of scarps, and the Bagno dell' Acqua.

The straightness and parallelism of the supposed fault-lines of Foerstner and Bergeat appear to me, after examination of the island and study of the large-scale chart, to be unduly emphasized. As a matter of fact, the inner scarp and ridge of Serra di Ghirlanda with its orogenic continuation in the Cuddioli dietro Isola is far from being a straight line, curving gently round from a north-north-westerly direction at the north end, through north-south, to northeast-southwest at the southern end. A similar curvature is shown by the Costa Zichidi ridge, and also at that of Costa di Zeneti, which latter turns sharply, but without any tectonic discontinuity, into the ridge and scarp of Cuddia Nera, with an east-west direction. The scarp of the summit of Montagna Grande, on the other hand, while in general following the lines of the Ghirlanda–Zichidi ridges and facing them, shows essentially straight lines: one on the east with a nearly north-south direction and the other east-west, the two meeting in a sharp angle at the southeast corner of the mountain, at the Rione Miliac. On the west, northwest, and north, however, the mass of Montagna Grande shows no scarps which correspond to those of Costa Zeneti and Cuddia Nera. Furthermore, the eastern slopes of Monte Gibelé slope gently down, with typical volcanic cone topography, to the Piano di Ghirlanda, whereas if the Ghirlanda scarp was due to faulting, and if Monte Gibelé is an originally integral part of the Montagna Grande mass, as there is good petrographic and orogenic reason to believe, we should expect Gibelé also to show fault scarps marking the line of separation from the surrounding region.

Again, it is difficult to conceive of the origin of the deep and narrow valleys surrounding Montagna Grande on the basis of either the fault or the upthrust theory. The one would explain them by the slipping down or differential movement of narrow

blocks, concentric about the central mass, a case which, so far as I know, is unparalleled elsewhere, especially on so small a scale; or the other as due to erosion along the fault zone, which is also difficult to accept in view of the relatively dry climate and the character of the surface-drainage topography.

Without desiring to be polemical, I may mention that the fault-lines mentioned by Foerstner, and indicated on the small map by Bergeat, seem to me to be somewhat arbitrary and subjective and their apparent parallelism rather forced by judicious choice. Thus, the most northeasterly connects the Bagno dell' Acqua (which can scarcely be regarded as a volcanic center) with a very minor part of the Montagna Grande scarp. That on the southwest connects the very minor Cuddia Sataria with a not very pronounced part of the coast line. That connecting Cuddia Sciuvechi and Monte Fosso del Russo might have been extended on the one side to Cuddia Gelkhamar and on the other to Cuddia Attalora with little deviation from a straight line. Also, they are arbitrary in their omissions. Thus, radiating lines might have been drawn from Cuddia Mida as a center toward the north, northwest, and west, each of which would have run through three or more volcanic cones, and such radiating lines would have been consonant with the radiating system of dikes observed about many volcanoes.

Author's views.—Accepting the hypothetical granitic basement, which is in harmony with observations on Linosa, I suppose that the first volcano (which presumably started in submarine eruptions like those in 1831 and 1891[1]) was a large one and covered the whole of the present area of the island, except possibly a small area at the northwest. The flows poured out by this volcano were of pantelleritic trachyte (Foerstner's "phonolite" and "later andesite") and of comendite (Foerstner's "liparite"), the now existent sheets of which formed the lower flanks of the old cone. On the west, at the Costa Zichidi and the Scauri district, they still show in places traces of the original lava surfaces. Later than these, but issuing from the same volcanic center, which may be supposed to have been probably between the Cuddia Mida and Monte Gibelé, were flows of green pantellerite (Foerstner's crystalline pantellerites), which

[1] Cf. H. S. Washington, *Am. Jour. Sci.*, XXVII (1909), 131.

covered most of the slopes of the old cone and are now seen in the southeast portion of the island and to the north and northwest of Montagna Grande. This original, large volcano was reduced to a large caldera with an encircling somma (about 6 kilometers in diameter), with gentle slopes toward the periphery but steep scarps on the inner side, either by an explosion or possibly by subsidence of the central portion, according to Stübel's theory. These are the scarps of Serra Ghirlanda, Costa Zichidi, Costa Zeneti, and Cuddia Nera. A similar history and a similar form at the end of the first stage of activity have been true of many well-known volcanoes, such as Santorini, Monte Vico near Viterbo, Somma-Vesuvius, Etna, Pico de Teyde, Taal, and many others. During this first phase and presumably before the formation of the caldera there were formed the parasitic cones of green pantellerite, notably those of Cuddia Attalora, Cuddia Gadir, Monte Sant' Elmo, and Cuddioli dietro Isola.

The eruptions of the second phase began within this caldera, the floor of which may have been below sea-level (as in the case of Santorini), and which was apparently breached to the north, between Cuddie Nera and Gadir. These consisted largely of trachyte (Foerstner's "older andesite"), which built up the great mass of Montagna Grande and Monte Gibelé. I follow Bergeat in thinking that the latter served as the vent for most of these eruptions, while Cuddia Mida may be regarded as a later parasitic cone near the summit of the volcano, which emitted mostly pantelleritic pumice. The trachytes of Monte Gibelé filled, or nearly filled, the large caldera, and are covered in many portions of the area with pumiceous lapilli derived from Cuddia Mida.

This pumiceous outburst may be regarded as the last of this phase, after which the northwestern part underwent a serious dislocation. The block which constitutes the present Montagna Grande was separated from the Gibelé portion by the Passo Khalchi fault, and tilted about an almost east-west axis. The southern end was raised some 250 meters or so, forming the prominent Miliac scarp and bringing the upper edge above the level of the former summit of Monte Gibilé. To the north the movement was downward, producing the depression of the Rione di Bagno now in part occupied by the lake.

That such a movement can have taken place on the island is shown by that preceding the submarine eruption of 1891 near the corner of the island, when a section of the northeast coast from Punta Karuscia to Punta Tracion was raised nearly one meter.[1] Such a tilting of a fault block explains reasonably the steep scarps, their presence only at one end of the mass, the revealed structure of sheets of columnar flows, and the general slope of the surface toward the north, while the simple set of two almost straight lines formed by the scarps is also in harmony with this interpretation.

Subsequent to this dislocation the second stage of the second phase took place in the formation of the small parasitic cones of Fosso del Russo, Monti Gibilé *a* and *b*, Cuddia Randazzo, Monte Gelfiser, and others, which poured out flows only of black pantellerite (Foerstner's vitreous pantellerite). It is noteworthy that all these small cones are found on the edges of the Montagna Grande block, just where the movement of the block would give exit to the magma along the fracture lines. None of them have broken through the main area of the mass, though it is uncertain whether Cuddia Sciuvechi, which also poured out black pantellerite, is along the western fracture line or on the slope of the original large volcano, and hence belonging to Phase I.

The southern cones of this period, Gibilé *a* and *b* and Russo, are of small size, and their flows are short and barely do more than reach the bottom of the old caldera flow, not getting as far as the opposite inner somma ring. The northern cones, on the contrary, Cuddie Randazzo and Gelfiser, are much larger, and their flows of much greater length and volume, Khagiar reaching the sea and Gelfiser coming up to the Zeneti scarp and apparently overflowing the northwest corner portion of the tilted block. It will be observed that this disposition is in harmony with the structural explanation here suggested.

According to this interpretation the Bagno dell' Acqua (with the alluvial Rione) is not a center of eruption, as supposed by Foerstner and Bergeat, but part of the old caldera floor, somewhat lowered by the block tilting, and left uncovered by the flows of Monte Gibelé and those following the Montagna Grande dislocation. This

[1] G. A. Butler, *Nature*, XLV (1891), 584.

explains its features better than does the view that it is due to an explosive eruption, surrounded as it is by the scarps of Costa Zeneti and Cuddia Nera on two sides, and the ends of the lava flows of Gelfiser and Khagiar and the slopes of the Montagna Grande mass on the others.

With the cessation of the outflows of black pantellerite, though after what interval we do not know, began the phase of basaltic eruptions, the earliest being apparently that which broke through the green pantellerite of Monte Sant' Elmo. These were comparatively small in volume and confined entirely to the northwest part of the island, though Foerstner mentions some basaltic dikes as occurring along the east coast. These eruptions formed the small,

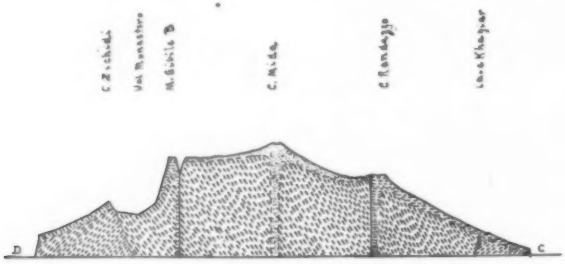


FIG. 4

scoriaceous cones already mentioned, and also gave rise to flows of basalt, which covered a large part of this portion of Pantelleria. The submarine eruption of 1891, four kilometers west of the harbor, is to be regarded as the last eruptive activity.[1]

Evidence of diminishing volcanicity is still manifest in fumaroles and hot springs. Of the former the most important are the Favara Grande and the Stufa di Khasen. The first is situated on the slope of Montagna Grande, northeast of Monte Fosso del Russo, at an altitude above sea-level of 410 meters. It consists of three openings in the rough lava, which emit scalding hot steam with a strong odor of sulphur dioxide, the rocks being deeply decomposed for some distance around. This fumarole is utilized by the goatherds for a

[1] H. S. Washington, *Am. Jour. Sci.*, XXVII (1909), 131.

supply of potable water by covering the openings with brushwood, which condenses the steam and gives rise to a variable trickle of water. The Stufa di Khasen is situated in the northwest corner of the island, near the Cuddie Rosse, and the vapors issue in a deep grotto, which was walled up and converted into a hot-vapor bath, apparently by the Arabs. There are other fumaroles below the Rione Miliac, at the summit of Montagna Grande, and in the crater of Cuddia Mida, as well as one, the Grotta di Bagno Asciutto, near Monte Gibilé *a*. The occurrence of these fumaroles around the Montagna Grande block is quite consonant with the presence

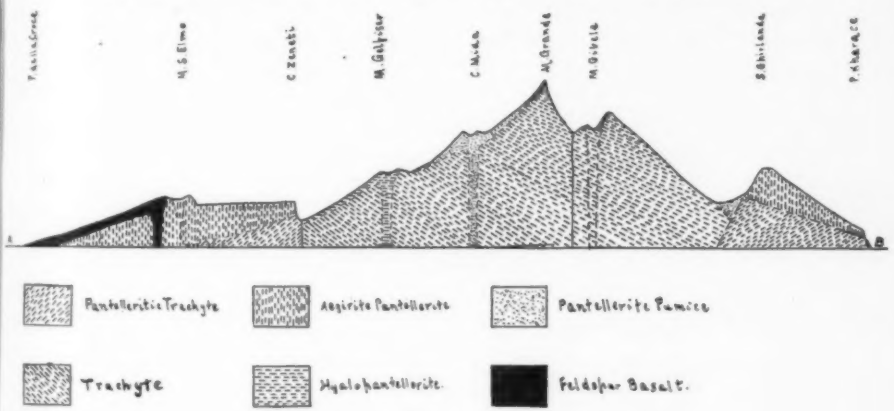


FIG. 5

of a line of fracture. The hot springs occur in various parts of the island, chiefly near the shore, while others are found at the southeast corner of the Bagno dell' Acqua. Foerstner gives two analyses, from which it appears that the waters of the lake are high in soda, with some potash, chiefly as chlorides, with less sulphates and carbonates.

To sum up, my idea of the volcanic succession may be briefly put thus:

Phase I: Building-up of a large cone, composed of flows of pantelleritic trachyte, comendite, and lastly green pantellerite. Attalora and Gadir and Monte Sant' Elmo are parasitic cones of this.

This phase was ended by an explosion, or possibly by a subsidence, blowing off the central and upper parts of the cone, forming a large caldera in the center, and leaving Serra di Ghirlanda, and Coste Zichidi, Monastero, Zeneti and Nera as a surrounding somma.

Phase II, Subphase 1: The building-up within the caldera of the Gibelé–Montagna Grande cone, with its crater probably that of Gibelé, the lavas being trachytes. Cuddia Mida was a parasitic vent, ejecting pantelleritic pumice, and the last eruptive crater of this subphase, which was concluded by the dislocation of the Montagna Grande block, which tilted up toward the south and down toward the north.

Subphase 2: The eruption of black pantellerite along the fracture line surrounding the tilted block, forming the Cuddie Randazzo, Gelfiser, Russo, and Gibilé *a* and *b*, with their flows.

Phase III: Eruption of basalts alone, formation of Cuddie Ferle, Brucciate, Foerstner Volcano (1891), etc. Fumaroles and hot springs.

These relations are shown in the accompanying sections (Figs. 4 and 5), in which the vertical scale is five times the horizontal.

LOG OF WELL OF PENNSYLVANIA SALT COMPANY DETROIT, MICH.

WILLIAM H. FRY[1]
U.S. Bureau of Soils, Washington, D.C.

This Bureau has recently prepared logs of various Michigan salt wells;[2] but unfortunately the samples from which the following log was prepared did not come in until too late to be incorporated with the other work. However, it is thought advisable to make the results complete, and consequently the log is given herewith:

Depth in Feet	
2– 52	Calcareous clay
52– 200	Limestone
200– 280	Calcareous sand
280– 400	Calcareous sand
400– 550	Limestone
550– 560	Limestone
560– 572	Limestone and gypsum
572– 620	Limestone
620– 700	Shaly limestone
700– 790	Limestone
790– 815	Salt
815– 840	Limestone
840– 920	Limestone
920– 950	Salt
950–1050	Limestone
1050–1085	Salt and limestone
1085–1165	Salt
1165–1175	Dolomitic and salty limestone
1175–1270	Salt
1270–1281	Salty limestone

[1] Scientist in Soil Laboratory Investigations, Bureau of Soils, U.S. Dept. Agric.

[2] See *Journal of Geology*, XXI, 320–22 (1913); and *Bulletin 94*, Bureau of Soils, U.S. Dept. of Agriculture.

Reviews

The Mining World Index of Current Literature. By Geo. E. Sisley. Chicago: Mining World Co., 1913. Pp. 234+xxiv. $1.00.

A comprehensive list of current literature of mining, metallurgy, and allied industries for the second half of 1912. The list is arranged alphabetically by authors. For each article the title, the periodical in which it appeared, the date of issue, the approximate number of words, and the price of the article are given. The general index is supplemented by an author index and a title index. In the catalogue proper papers are grouped under the following heads: "Metals and Metal Ores," "Non-Metals," "Mines and Mining," "Mill and Milling," "Power and Machinery," "Miscellaneous." The value of such a reference work is so obvious as to require no comment.

A. D. B.

Mineralogical Notes, Series 1 and 2. By Waldemar T. Schaller. Washington, 1911, 1912. U.S. Geol. Survey Bulls. No. 490, pp. 109, figs. 14, and No. 509, pp. 115, figs. 5, pl. I.

The author includes in these two bulletins notes on crystal measurements and chemical analyses of a number of mineral species—some forty papers in all. The material is of interest chiefly to the mineralogist and crystallographer. It appears to be the beginning of a new series of papers to be issued as bulletins of the Geological Survey.

A. D. B.

Determinative Mineralogy. By J. Volney Lewis. New York: John Wiley & Sons, 1913. Pp. 151, figs. 68. $1.50.

This book follows the general plan of Brush-Penfield, with some changes in arrangement, considerable condensation, and the elimination of the rarer minerals. These changes seem to be decidedly advantageous for ordinary determinative laboratory work. The key is not so well arranged for very rapid work as Moses and Parsons; but this is more than outweighed by the greater completeness of Lewis' tables.

In the reviewer's opinion it is by far the most satisfactory determinative work that has appeared in recent years, and should quickly find its place in many laboratories.

A. D. B.

Recent Publications

OF

The University of Chicago Press

Chicago and the Old Northwest, 1673–1835. By Milo Milton Quaife, Professor of History in the Lewis Institute of Technology.

488 pages, 8vo, cloth; $4.00, postpaid $4.23

This book recounts, in a manner at once scholarly and dramatic, the early history of Chicago. Important as this subject is, it is not treated solely for its own sake. The author's larger purpose has been to trace the evolution of the frontier from savagery to civilization. From the point of view of Chicago and the Northwest alone the work is local in character, although the locality concerned embraces five great states of the Union; in the larger sense its interest is as broad as America, for every foot of America has been at some time on the frontier of civilization.

This task has never before been performed in an adequate way. The one really brilliant historian of Illinois, Mr. Edward G. Mason, died with only a few fragments of his great work completed, and no one has yet come forward to take his place. It is believed that this book will take rank as the standard history of Chicago in the early days.

Chicago Tribune. A history of the beginnings of Chicago which, because it is scientific and based upon records rather than upon tradition, may overturn existing chronologies on the same subject.

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In several chapters animal communities of lakes, streams, swamps, forests, prairies, and various soils and topographic situations are considered from the point of view of modern dynamic ecology. A very valuable feature of the book is the

three hundred figures of widely distributed animals chosen to represent the chief types of animal communities and their characteristic modes of life.

Artificial Parthenogenesis and Fertilization. By Jacques Loeb, Member of the Rockefeller Institute for Medical Research.

318 pages, 12mo, cloth; $2.50, postpaid $2.68

This new work presents the first complete treatment of the subject of artificial parthenogenesis in English. Professor Loeb published four years ago a book in German under the title *Die chemische Entwicklungserregung des tierischen Eies.* Mr. W. O. R. King, of the University of Leeds, England, translated the book into English, and the translation has been revised, enlarged, and brought up to date by Professor Loeb. It gives, as the author says in the preface, an account of the various methods by which unfertilized eggs can be caused to develop by physico-chemical means, and the conclusions which can be drawn from them concerning the mechanism by which the spermatozoon induces development. Since the problem of fertilization is intimately connected with so many different problems of physiology and pathology, the bearing of the facts recorded and discussed in the book goes beyond the special problem indicated by the title.

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C. E. Raymond, Vice-President of the J. Walter Thompson Co. It seems to me to be the most comprehensive and comprehensible of any of the works on this subject which I have had the pleasure of seeing.

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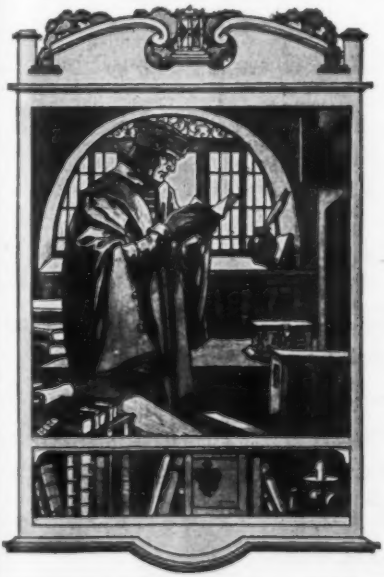

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No. I, p. 30 (article by Warren D. Smith): In the bottom paragraph, "because the northern part of Luzon has been longest *under* water" should read, "because the northern part of Luzon has been longest *above* water."

The title of the map (p. 31) should read: Map Showing Physiographic Districts of Luzon.